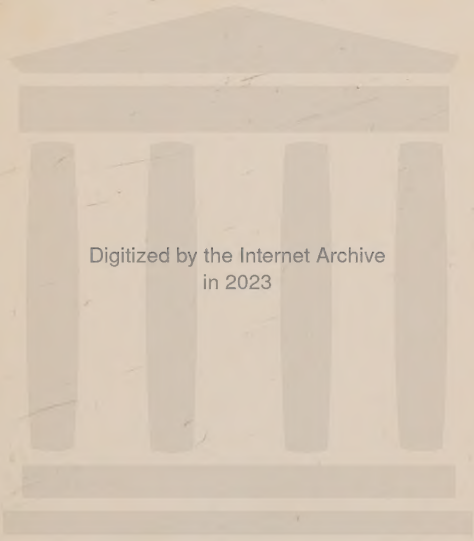
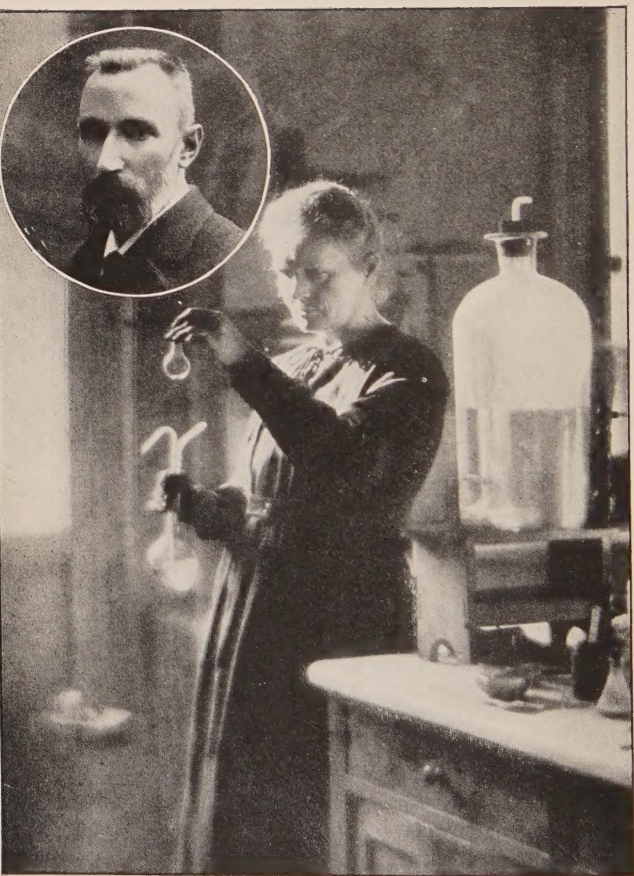


THE STORY
OF
MODERN SCIENCE

HENRY SMITH WILLIAMS



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MADAME CURIE AND THE LATE PIERRE CURIE

THE STORY OF MODERN SCIENCE

By
HENRY SMITH WILLIAMS

IN TEN VOLUMES
ILLUSTRATED

VOLUME II

EXPLORING THE
ATOM



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*The Story
of
Modern Science*

VOLUME II

EXPLORING THE ATOM

EXPLORING THE ATOM

CHAPTER I

THE RISE OF MODERN CHEMISTRY

OF all the contests that were waged in the various fields of science in the iconoclastic epoch that closed the eighteenth century, perhaps the fiercest and most turbulent was that which fell within the field of chemistry. Indeed, this was one of the most memorable warfares in the history of polemics. It was a battle veritably Napoleonic in its inception, scope, and incisiveness. As was fitting, it was a contest of France against the world; but the Napoleonic parallel fails before the end, for in this case France won not only speedily and uncompromisingly, but for all time.

The main point at issue concerned the central doctrine of the old chemistry—the doctrine of Becher and Stahl, that the only combustible substance in nature is a kind of matter called phlogiston, which enters into the composition of other bodies in varying degree, thus determining their inflammability. This theory seems crude enough now, since we know that phlogiston was a purely fictitious element, yet it served an excellent purpose when it was propounded and it held its place as the central doctrine of chemical philosophy for almost a century.

At the time when this theory was put forward, it must be recalled, the old Aristotelian idea that

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the four primal elements are earth, air, fire, and water still held sway as the working foundation of all chemical philosophies. Air and water were accepted as simple bodies. Only a few acids and alkalies were known, and these but imperfectly; and the existence of gases as we now know them, other than air, was hardly so much as suspected. All the known facts of chemistry seemed then to harmonize with the phlogiston hypothesis; and so, later on, did the new phenomena which were discovered in such profusion during the third quarter of the eighteenth century—the epoch of pneumatic chemistry. Hydrogen gas, discovered by Cavendish in 1776, and called inflammable air, was thought by some chemists to be the very principle of phlogiston itself. Other “airs” were adjudged “dephlogisticated” or “phlogisticated,” in proportion as they supported or failed to support combustion. The familiar fact of a candle flame going out when kept in a confined space of ordinary air was said to be due to the saturation of this air with phlogiston. And all this seemed to tally beautifully with the prevailing theory.

But presently the new facts began, as new facts always will, to develop an iconoclastic tendency. The phlogiston theory had dethroned fire from its primacy as an element by alleging that flame is due to a union of the element heat with the element phlogiston. Now earths were decomposed, air and water were shown to be compound bodies, and at last the existence of phlogiston itself was to be called in question. The structure of the old chemical philosophy had been completely riddled; it was now to be overthrown. The culminating observation which brought matters to a crisis was

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the discovery of oxygen, which was made by Priestley in England and Scheele in Sweden, working independently, in the year 1774. Priestley called the new element "dephlogisticated air"; Scheele called it "empyreal air."

But neither Priestly nor Scheele realized the full import of this discovery; nor, for that matter, did any one else at the moment. Very soon, however, one man at least had an inkling of it. This was the great French chemist Antoine Laurent Lavoisier. It has sometimes been claimed that he himself discovered oxygen independently of Priestley and Scheele. At all events, he at once began experimenting with it, and very soon it dawned upon him that this remarkable substance might furnish a key to the explanation of many of the puzzles of chemistry. He found that oxygen is consumed or transformed during the combustion of any substance in air. He reviewed the phenomena of combustion in the light of this new knowledge. It seemed to him that the new element explained them all without aid of the supposititious element phlogiston. What proof, then, have we that phlogiston exists? Very soon he is able to answer that there is no proof, no reason to believe that it exists. Then why not denounce phlogiston as a myth, and discard it from the realm of chemistry?

Precisely this is what Lavoisier purposes to do. He associates with him three other famous French chemists, Berthollet, Guyton de Morveau, and Fourcroy, and sets to work to develop a complete system of chemistry based on the new conception. In 1788 the work is completed and given to the world. It is not merely an epoch-making book;

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it is revolutionary. It discards phlogiston altogether, alleging that the elements really concerned in combustion are oxygen and heat. It claims that acids are compounds of oxygen with a base, instead of mixtures of "earth" and water; that metals are simple elements, not compounds of "earth" and "phlogiston"; and that water itself, like air, is a compound of oxygen with another element.

In applying these ideas the new system proposes an altogether new nomenclature for chemical substances. Hitherto the terminology of the science has been a matter of whim and caprice. Such names as "liver of sulfur," "mercury of life," "horned moon," "the double secret," "the salt of many virtues," and the like, have been accepted without protest by the chemical world. With such a terminology continued progress was as impossible as human progress without speech. The new chemistry of Lavoisier and his *confrères*, following the model set by zoology half a century earlier, designates each substance by a name instead of a phrase, applies these names according to fixed rules, and, in short, classifies the chemical knowledge of the time and brings it into a system, lacking which no body of knowledge has full title to the name of science.

Tho Lavoisier was not alone in developing this revolutionary scheme, posterity remembers him as its originator. His dazzling and comprehensive genius obscured the feebler lights of his *confrères*. Perhaps, too, his tragic fate was not without influence in augmenting his posthumous fame. In 1794 he fell by the guillotine, guiltless of any crime but patriotism—a victim of the

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"Reign of Terror." "The Republic has no need of *savants*," remarked the functionary who signed the death-warrant of the most famous chemist of the century.

The leader of the reform movement in chemistry thus died at the hands of bigotry and fanaticism—rather, let us say, as the victim of a national frenzy—while the cause he championed was young, yet not too soon to see the victory as good as won. The main body of French chemists had accepted the new doctrines almost from the first, and elsewhere the opposition had been of that fierce, eager type which soon exhausts itself in the effort. At Berlin they began by burning Lavoisier in effigy, but they ended speedily by accepting the new theories. In England the fight was more stubborn, but equally decisive. At first the new chemistry was opposed by such great men as Black, of "latent heat" fame; Rutherford, the discoverer of nitrogen; and Cavendish, the inventor of the pneumatic trough and the discoverer of the composition of water, not to mention a coterie of lesser lights; but one by one they wavered and went over to the enemy. Oddly enough, the doughtiest and most uncompromising of all the champions of the old "phlogistic" ideas was Dr. Priestley, the very man whose discovery of oxygen had paved the way for the "antiphlogistic" movement—a fact which gave rise to Cuvier's remark that Priestley was undoubtedly one of the fathers of modern chemistry, but a father who never wished to recognize his daughter.

A most extraordinary man was this Dr. Priestley. Davy said of him, a generation later, that no other person ever discovered so many new and

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curious substances as he; yet to the last he was only an amateur in science, his profession being the ministry. There is hardly another case in history of a man not a specialist in science accomplishing so much in original research as did Joseph Priestley, the chemist, physiologist, electrician; the mathematician, logician, and moralist; the theologian, mental philosopher, and political economist. He took all knowledge for his field; but how he found time for his numberless researches and multifarious writings, along with his every-day duties, must ever remain a mystery to ordinary mortals.

That this marvelously receptive, flexible mind should have refused acceptance to the clearly logical doctrines of the new chemistry seems equally inexplicable. But so it was. To the very last, after all his friends had capitulated, Priestley kept up the fight. From America, whither he had gone to live in 1794, he sent out the last defî to the enemy in 1800, in a brochure entitled "The Doctrine of Phlogiston Upheld," etc. In the mind of its author this was little less than a pæan of victory; but all the world besides knew that it was the swan-song of the doctrine of phlogiston. Despite the defiance of this single warrior the battle was really lost and won, and as the century closed, "antiphlogistic" chemistry had practical possession of the field.

THE COMING OF DALTON

Small beginnings have great endings—sometimes. As a case in point, note what came of the small original effort of a self-trained back-country Quaker youth named John Dalton, who along

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towards the close of the last century became interested in the weather, and was led to construct and use a crude rain-gage to test the amount of the waterfall. The simple experiments thus inaugurated led to no fewer than two hundred thousand recorded observations regarding the weather, which formed the basis for some of the most epochal discoveries in meteorology, as we have seen. But this was only a beginning. The simple rain-gage pointed the way to the most important generalization of our century in a field of science with which, to the casual observer, it might seem to have no alliance whatever. The wonderful theory of atoms, on which the whole gigantic structure of modern chemistry is founded, was the logical outgrowth, in the mind of John Dalton, of those early studies in meteorology.

The way it happened was this: From studying the rainfall, Dalton turned naturally to the complementary process of evaporation. He was soon led to believe that vapor exists in the atmosphere as an independent gas. But since two bodies can not occupy the same space at the same time, this implies that the various atmospheric gases are really composed of discrete particles. These ultimate particles are so small that we can not see them—can not, indeed, more than vaguely imagine them—yet each particle of vapor, for example, is just as much a portion of water as if it were a drop out of the ocean, or, for that matter, the ocean itself. But again, water is a compound substance, for it may be separated, as Cavendish had shown, into the two elementary substances hydrogen and oxygen. Hence the atom of water must be composed of two lesser atoms joined together.

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Imagine an atom of hydrogen and one of oxygen. Unite them, and we have an atom of water; sever them, and the water no longer exists; but whether united or separate the atoms of hydrogen and of oxygen remain hydrogen and oxygen and nothing else. Differently mixed together or united, atoms produce different gross substances; but the elementary atoms never change their chemical nature—their distinct personality.

It was about the year 1803 that Dalton first gained a full grasp of the conception of the chemical atom. At once he saw that the hypothesis, if true, furnished a marvelous key to secrets of matter hitherto insoluble—questions relating to the relative proportions of the atoms themselves. It is known, for example, that a certain bulk of hydrogen gas unites with a certain bulk of oxygen gas to form water. If it be true that this combination consists essentially of the union of atoms one with another (each single atom of hydrogen united to a single atom of oxygen), then the relative weights of the original masses of hydrogen and of oxygen must be also the relative weights of each of their respective atoms. If one pound of hydrogen unites with five and one-half pounds of oxygen (as, according to Dalton's experiments, it did), then the weight of the oxygen atom must be five and one-half times that of the hydrogen atom. Other compounds may plainly be tested in the same way. Dalton made numerous tests before he published his theory. He found that hydrogen enters into compounds in smaller proportions than any other element known to him, and so, for convenience, determined to take the weight of the hydrogen atom as unity. The atomic

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weight of oxygen then becomes (as given in Dalton's first table of 1803) 5.5; that of water (hydrogen plus oxygen) being of course 6.5. The atomic weights of about a score of substances are given in Dalton's first paper, which was read before the Literary and Philosophical Society of Manchester, October 21, 1803. I wonder if Dalton himself, great and acute intellect tho he had, suspected, when he read that paper, that he was inaugurating one of the most fertile movements ever entered on in the whole history of science?

Be that as it may, it is certain enough that Dalton's contemporaries were at first little impressed with the novel atomic theory. Just at this time, as it chanced, a dispute was waging in the field of chemistry regarding a matter of empirical fact which must necessarily be settled before such a theory as that of Dalton could ever hope for a hearing. This was the question whether or not chemical elements unite with one another always in definite proportions. Berthollet, the great co-worker with Lavoisier, and now the most authoritative of living chemists, contended that substances combine in almost indefinitely graded proportions between fixed extremes. He held that solution is really a form of chemical combination—a position which, if accepted, left no room for argument.

But his contention of the master was most actively disputed, in particular by Louis Joseph Proust, and all chemists of repute were obliged to take sides with one or the other. For a time the authority of Berthollet held out against the facts, but at last accumulated evidence told for Proust and his followers, and towards the close of the

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first decade of our century it came to be generally conceded that chemical elements combine with one another in fixed and definite proportions.

More than that: As the analysts were led to weigh carefully the quantities of combining elements, it was observed that the proportions are not only definite, but that they bear a very curious relation to one another. If element A combines with two different proportions of element B to form two compounds, it appeared that the weight of the larger quantity of B is an exact multiple of that of the smaller quantity. This curious relation was noticed by Dr. Wollaston, one of the most accurate of observers, and a little later it was confirmed by Johan Jakob Berzelius, the great Swedish chemist, who was to be a dominating influence in the chemical world for a generation to come. But this combination of elements in numerical proportions was exactly what Dalton had noticed as early as 1802, and what had led him directly to the atomic weights. So the confirmation of this essential point by chemists of such authority gave the strongest confirmation to the atomic theory.

During these same years the rising authority of the French chemical world, Joseph Louis Gay-Lussac, was conducting experiments with gases, which he had undertaken at first in conjunction with Humboldt, but which later on were conducted independently. In 1809, the next year after the publication of the first volume of Dalton's *New System of Chemical Philosophy*, Gay-Lussac published the results of his observations, and among other things brought out the remarkable fact that gases, under the same conditions

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as to temperature and pressure, combine always in definite numerical proportions as to volume. Exactly two volumes of hydrogen, for example, combine with one volume of oxygen to form water. Moreover, the resulting compound gas always bears a simple relation to the combining volumes. In the case just cited the union of two volumes of hydrogen and one of oxygen results in precisely two volumes of water vapor.

Naturally enough the champions of the atomic theory seized upon these observations of Gay-Lussac as lending strong support to their hypothesis—all of them, that is, but the curiously self-reliant and self-sufficient author of the atomic theory himself, who declined to accept the observations of the French chemist as valid. Yet the observations of Gay-Lussac were correct, as countless chemists since then have demonstrated anew, and his theory of combination by volumes became one of the foundation-stones of the atomic theory, despite the opposition of the author of that theory.

The true explanation of Gay-Lussac's law of combination by volumes was thought out almost immediately by an Italian savant, Amadeo Avogadro, and expressed in terms of the atomic theory. The fact must be, said Avogadro, that under similar physical conditions every form of gas contains exactly the same number of ultimate particles in a given volume. Each of these ultimate physical particles may be composed of two or more atoms (as in the case of water regards the amount of space that separates it vapor), but such a compound atom conducts itself as if it were a simple and indivisible atom, as

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from its fellows under given conditions of pressure and temperature. The compound atom, composed of two or more elementary atoms, Avogadro proposed to distinguish, for purposes of convenience, by the name molecule. It is to the molecule, considered as the unit of physical structure, that Avogadro's law applies.

This vastly important distinction between atoms and molecules, implied in the law just expressed, was published in 1811. Four years later, the famous French physicist Ampère outlined a similar theory, and utilized the law in his mathematical calculations. And with that the law of Avogadro dropped out of sight for a full generation. Little suspecting that it was the very key to the inner mysteries of the atoms for which they were seeking, the chemists of the time cast it aside, and let it fade from the memory of their science.

This, however, was not strange, for of course the law of Avogadro is based on the atomic theory, and in 1811 the atomic theory was itself still being weighed in the balance. The law of multiple proportions found general acceptance as an empirical fact; but many of the leading lights of chemistry still looked askance at Dalton's explanation of this law. Thus Wollaston, tho from the first inclined to acceptance of the Daltonian view, cautiously suggested that it would be well to use the non-committal word "equivalent" instead of "atom"; and Davy, for a similar reason, in his book of 1812, speaks only of "proportions," binding himself to no theory as to what might be the nature of these proportions.

At least two great chemists of the time, how-

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ever, adopted the atomic view with less reservation. One of these was Thomas Thomson, professor at Edinburgh, who in 1807 had given an outline of Dalton's theory in a widely circulated book, which first brought the theory to the general attention of the chemical world. The other, and even more noted advocate of the atomic theory, was Johan Jakob Berzelius. This great Swedish chemist at once set to work to put the atomic theory to such tests as might be applied in the laboratory. He was an analyst of the utmost skill, and for years he devoted himself to the determination of the combining weights, "equivalents," or "proportions" of the different elements. These determinations, in so far as they were accurately made, were simple expressions of empirical facts, independent of any theory; but gradually it became more and more plain that these facts all harmonize with the atomic theory of Dalton. So by common consent the proportionate combining weights of the elements came to be known as atomic weights—the name Dalton had given them from the first—and the tangible conception of the chemical atom as a body of definite constitution and weight gained steadily in favor.

From the outset the idea had had the utmost tangibility in the mind of Dalton. He had all along represented the different atoms by geometrical symbols—as a circle for oxygen, a circle enclosing a dot for hydrogen, and the like—and had represented compounds by placing these symbols of the elements in juxtaposition. Berzelius proposed to improve upon this method by substituting for the geometrical symbol the initial of the Latin name of the element represented—O

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for oxygen, H for hydrogen, and so on—a numerical coefficient to follow the letter as an indication of the number of atoms present in any given compound. This simple system soon gained general acceptance, and with slight modifications it is still universally employed. Every schoolboy now is aware that H_2O is the chemical way of expressing the union of two atoms of hydrogen with one of oxygen to form a molecule of water. But such a formula would have had no meaning for the wisest chemist before the day of Berzelius.

The universal fame of the great Swedish authority served to give general currency to his symbols and atomic weights, and the new point of view thus developed led presently to two important discoveries which removed the last lingering doubts as to the validity of the atomic theory. In 1819 two French physicists, Dulong and Petit, while experimenting with heat, discovered that the specific heats of solids (that is to say, the amount of heat required to raise the temperature of a given mass to a given degree) vary inversely as their atomic weights. In the same year Eilhard Mitscherlich, a German investigator, observed that compounds having the same number of atoms to the molecule are disposed to form the same angles of crystallization—a property which he called isomorphism.

Here, then, were two utterly novel and independent sets of empirical facts which harmonize strangely with the supposition that substances are composed of chemical atoms of a determinate weight. This surely could not be coincidence—it tells of law. And so as soon as the claims of Dulong and Petit and of Mitscherlich had been

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substantiated by other observers, the laws of the specific heat of atoms, and of isomorphism, took their place as new levers of chemical science. With the aid of these new tools an impregnable breastwork of facts was soon piled about the atomic theory. And John Dalton, the author of that theory, plain, provincial Quaker, working on to the end in semi-retirement, became known to all the world and for all time as a master of masters.

HUMPHREY DAVY AND ELECTROCHEMISTRY

During those early years of our century, when Dalton was grinding away at chemical fact and theory in his obscure Manchester laboratory, another Englishman held the attention of the chemical world with a series of the most brilliant and widely heralded researches. Humphry Davy had come to London in 1801, at the instance of Count Rumford, to assume the chair of chemical philosophy in the Royal Institution, which the famous American had just founded.

Here, under Davy's direction, the largest voltaic battery yet constructed had been put in operation, and with its aid the brilliant young experimenter was expected almost to perform miracles. And indeed he scarcely disappointed the expectation, for with the aid of his battery he transformed so familiar a substance as common potash into a metal which was not only so light that it floated on water, but possessed the seemingly miraculous property of bursting into flames as soon as it came in contact with that fire-quenching liquid. If this were not a miracle, it had for the popular eye all the appearance of the miraculous.

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What Davy really had done was to decompose the potash, which hitherto had been supposed to be elementary, liberating its oxygen, and thus isolating its metallic base, which he named potassium. The same thing was done with soda, and the closely similar metal sodium was discovered—metals of a unique type, possessed of a strange avidity for oxygen, and capable of seizing on it even when it is bound up in the molecules of water. Considered as mere curiosities, these discoveries were interesting, but aside from that they were of great theoretical importance, because they showed the compound nature of some familiar chemicals that had been regarded as elements. Several other elementary earths met the same fate when subjected to the electrical influence, the metals barium, calcium, and strontium being thus discovered. Thereafter Davy always referred to the supposed elementary substances (including oxygen, hydrogen, and the rest) as “undecomposed” bodies. These resist all present efforts to decompose them, but how can one know what might not happen were they subjected to an influence, perhaps some day to be discovered, which exceeds the battery in power as the battery exceeds the blow-pipe?

Another and even more important theoretical result that flowed from Davy's experiments during this first decade of the century was the proof that no elementary substances other than hydrogen and oxygen are produced when pure water is decomposed by the electric current. It was early noticed by Davy and others that when a strong current is passed through water, alkalis appear at one pole of the battery and acids at the other,

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and this tho the water used were absolutely pure. This seemingly told of the creation of elements—a transmutation but one step removed from the creation of matter itself—under the influence of the new “force.” It was one of Davy’s greatest triumphs to prove, in the series of experiments recorded in his famous Bakerian lecture of 1806, that the alleged creation of elements did not take place, the substances found at the poles of the battery having been dissolved from the walls of the vessels in which the water experimented upon had been placed. Thus the same implement which had served to give a certain philosophical warrant to the fading dreams of alchemy banished those dreams peremptorily from the domain of present science.

Tho the presence of the alkalies and acids in the water was explained, however, their respective migrations to the negative and positive poles of the battery remained to be accounted for. Davy’s classical explanation assumed that different elements differ among themselves as to their electrical properties, some being positively, others negatively, electrified. Electricity and “chemical affinity,” he said, apparently are manifestations of the same force, acting in the one case on masses, in the other on particles. Electro-positive particles unite with electro-negative particles to form chemical compounds, in virtue of the familiar principle that opposite electricities attract one another. When compounds are decomposed by the battery, this mutual attraction is overcome by the stronger attraction of the poles of the battery itself.

This theory of binary composition of all chemi-

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cal compounds, through the union of electro-positive and electro-negative atoms or molecules, was extended by Berzelius, and made the basis of his famous system of theoretical chemistry. This theory held that all inorganic compounds, however complex their composition, are essentially composed of such binary combinations. For many years this view enjoyed almost undisputed sway. It received what seemed strong confirmation when Faraday showed the definite connection between the amount of electricity employed and the amount of decomposition produced in the so-called electrolyte. But its claims were really much too comprehensive, as subsequent discoveries proved.

ORGANIC CHEMISTRY AND THE IDEA OF THE MOLECULE

When Berzelius first promulgated his binary theory he was careful to restrict its unmodified application to the compounds of the inorganic world. At that time, and for a long time thereafter, it was supposed that substances of organic nature had some properties that kept them aloof from the domain of inorganic chemistry. It was little doubted that a so-called "vital force" operated here, replacing or modifying the action of ordinary "chemical affinity." It was, indeed, admitted that organic compounds are composed of familiar elements—chiefly carbon, oxygen, hydrogen, and nitrogen—but these elements were supposed to be united in ways that could not be imitated in the domain of the non-living. It was regarded almost as an axiom of chemistry that no organic compound whatever could be put together from its elements—synthesized—in the

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laboratory. To effect the synthesis of even the simplest organic compound it was thought that the "vital force" must be in operation.

Therefore a veritable sensation was created in the chemical world when, in the year 1828, it was announced that the young German chemist Friedrich Wöhler, formerly pupil of Berzelius, and already known as a coming master, had actually synthesized the well-known organic product urea in his laboratory at Sacrow. The "exception which proves the rule" is something never heard of in the domain of logical science. Natural law knows no exceptions. So the synthesis of a single organic compound sufficed at a blow to break down the chemical barrier which the imagination of the fathers of the science had erected between animate and inanimate nature. Thenceforth the philosophical chemist would regard the plant and animal organisms as chemical laboratories in which conditions are peculiarly favorable for building up complex compounds of a few familiar elements, under the operation of universal chemical laws. The chimera "vital force" could no longer gain recognition in the domain of chemistry.

Now a wave of interest in organic chemistry swept over the chemical world, and soon the study of carbon compounds became as much the fashion as electrochemistry had been in the preceding generation.

Foremost among the workers who rendered this epoch of organic chemistry memorable were Justus Liebig in Germany and Jean Baptiste André Dumas in France, and their respective pupils, Charles Frédéric Gerhardt and Augustus

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Laurent. Wöhler, too, must be named in the same breath, as also must Louis Pasteur, who, tho somewhat younger than the others, came upon the scene in time to take chief part in the most important of the controversies that grew out of their labors.

Several years earlier than this the way had been paved for the study of organic substances by Gay-Lussac's discovery, made in 1815, that a certain compound of carbon and nitrogen, which he named cyanogen, has a peculiar degree of stability which enables it to retain its identity, and enter into chemical relations after the manner of a simple body. A year later Ampère discovered that nitrogen and hydrogen, when combined in certain proportions to form what he called ammonium, have the same property. Berzelius had seized upon this discovery of the compound radical, as it was called, because it seemed to lend aid to his dualistic theory. He conceived the idea that all organic compounds are binary unions of various compound radicals with an atom of oxygen, announcing this theory in 1818. Ten years later, Liebig and Wöhler undertook a joint investigation which resulted in proving that compound radicals are indeed very abundant among organic substances. Thus the theory of Berzelius seemed to be substantiated, and organic chemistry came to be defined as the chemistry of compound radicals.

But even in the day of its seeming triumph the dualistic theory was destined to receive a rude shock. This came about through the investigations of Dumas, who proved that in a certain organic substance an atom of hydrogen

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may be removed, and an atom of chlorine substituted in its place without destroying the integrity of the original compound—much as a child might substitute one block for another in its play house. Such a substitution would be quite consistent with the dualistic theory, were it not for the very essential fact that hydrogen is a powerfully electro-positive element, while chlorine is as strongly electro-negative. Hence the compound radical which united successively with these two elements must itself be at one time electro-positive, at another electro-negative—a seeming inconsistency which threw the entire Berzelian theory into disfavor.

In its place there was elaborated, chiefly through the efforts of Laurent and Gerhardt, a conception of the molecule as a unitary structure, built up through the aggregation of various atoms, in accordance with “elective affinities” whose nature is not yet understood. A doctrine of “nuclei” and a doctrine of “types” of molecular structure were much exploited, and, like the doctrine of compound radicals, became useful as aids to memory and guides for the analyst, indicating some of the plans of molecular construction, tho by no means penetrating the mysteries of chemical affinity. They are classifications rather than explanations of chemical unions. But at least they served an important purpose in giving definiteness to the idea of a molecular structure built of atoms as the basis of all substances.

Now at last the word molecule came to have a distinct meaning, as distinct from “atom,” in the minds of the generality of chemists, as it had had for Avogadro a third of a century be-

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fore. Avogadro's hypothesis that there are equal numbers of these molecules in equal volumes of gases, under fixed conditions, was revived by Gerhardt, and a little later, under the championship of Cannizzaro, was exalted to the plane of a fixed law. Thenceforth the conception of the molecule was to be as dominant a thought in chemistry as the idea of the atom had become in a previous epoch.

CHEMICAL AFFINITY

Of course the atom itself was in no sense displaced, but Avogadro's law soon made it plain that the atom had often usurped territory that did not really belong to it. In many cases the chemists had supposed themselves dealing with atoms as units where the true unit was the molecule. In the case of elementary gases, such as hydrogen and oxygen, for example, the law of equal numbers of molecules in equal spaces made it clear that the atoms do not exist isolated, as had been supposed.

Since two volumes of hydrogen unite with one volume of oxygen to form two volumes of water vapor, the simplest mathematics shows, in the light of Avogadro's law, not only that each molecule of water must contain two hydrogen atoms (a point previously in dispute), but that the original molecules of hydrogen and oxygen must have been composed in each case of two atoms—else how could one volume of oxygen supply an atom for every molecule of two volumes of water?

What, then, does this imply? Why, that the elementary atom has an avidity for other atoms,

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a longing for companionship, an "affinity"—call it what you will—which is bound to be satisfied if other atoms are in the neighborhood. Placed solely among atoms of its own kind, the oxygen atom seizes on a fellow oxygen atom, and in all their mad dancings these two mates cling together—possibly revolving about one another in miniature planetary orbits. Precisely the same thing occurs among the hydrogen atoms. But now suppose the various pairs of oxygen atoms come near other pairs of hydrogen atoms (under proper conditions which need not detain us here), then each oxygen atom loses its attachment for its fellow, and flings itself madly into the circuit of one of the hydrogen couplets, and—presto!—there are only two molecules for every three there were before, and free oxygen and hydrogen have become water. The whole process, stated in chemical phraseology, is summed up in the statement that under the given conditions the oxygen atoms had a greater affinity for the hydrogen atoms than for one another.

As chemists studied the actions of various kinds of atoms, in regard to their unions with one another to form molecules, it gradually dawned upon them that not all elements are satisfied with the same number of companions. Some elements ask only one, and refuse to take more; while others link themselves, when occasion offers, with two, three, four, or more. Thus we saw that oxygen forsook a single atom of its own kind and linked itself with two atoms of hydrogen. Clearly, then, the oxygen atom, like a creature with two hands, is able to clutch two other atoms. But we have no proof that under any circumstances it could

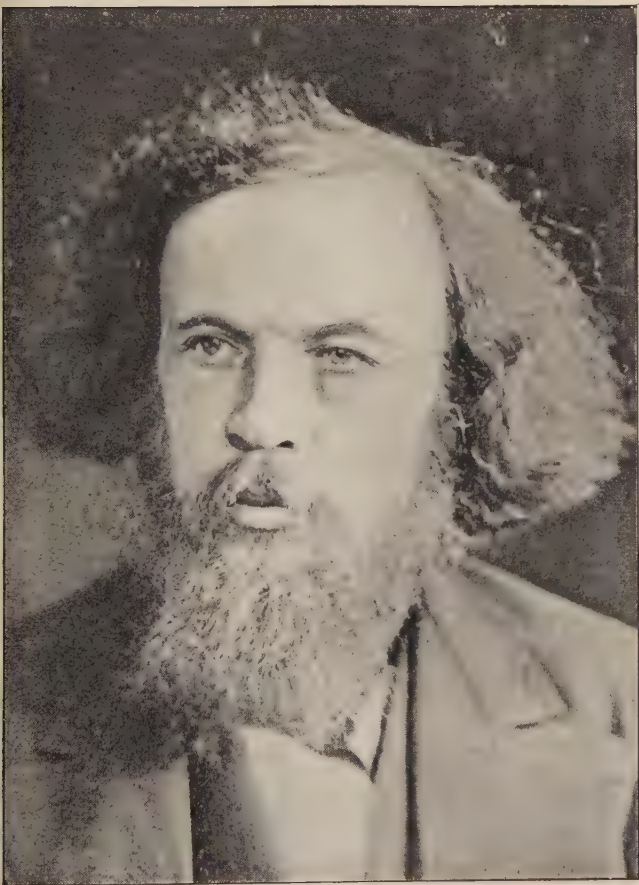
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hold more than two. Its affinities seem satisfied when it has two bonds. But, on the other hand, the atom of nitrogen is able to hold three atoms of hydrogen, and does so in the molecule of ammonium (NH_3); while the carbon atom can hold four atoms of hydrogen or two atoms of oxygen.

Evidently, then, one atom is not always equivalent to another atom of a different kind in combining powers. A recognition of this fact by Frankland about 1852, and its further investigation by others (notably A. Kekulé and A. S. Couper), led to the introduction of the word equivalent into chemical terminology in a new sense, and in particular to an understanding of the affinities or "valency" of different elements, which proved of the most fundamental importance.

Thus it was shown that, of the four elements that enter most prominently into organic compounds, hydrogen can link itself with only a single bond to any other element—it has, so to speak, but a single hand with which to grasp—while oxygen has capacity for two bonds, nitrogen for three (possibly for five), and carbon for four. The words monovalent, divalent, trivalent, tetravalent, etc., were coined to express this most important fact, and the various elements came to be known as monads, diads, triads, etc.

Just why different elements should differ thus in valency no one as yet knows; it is an empirical fact that they do. And once the nature of any element has been determined as regards its valency, a most important insight into the possible behavior of that element has been secured. Thus a consideration of the fact that hydrogen is

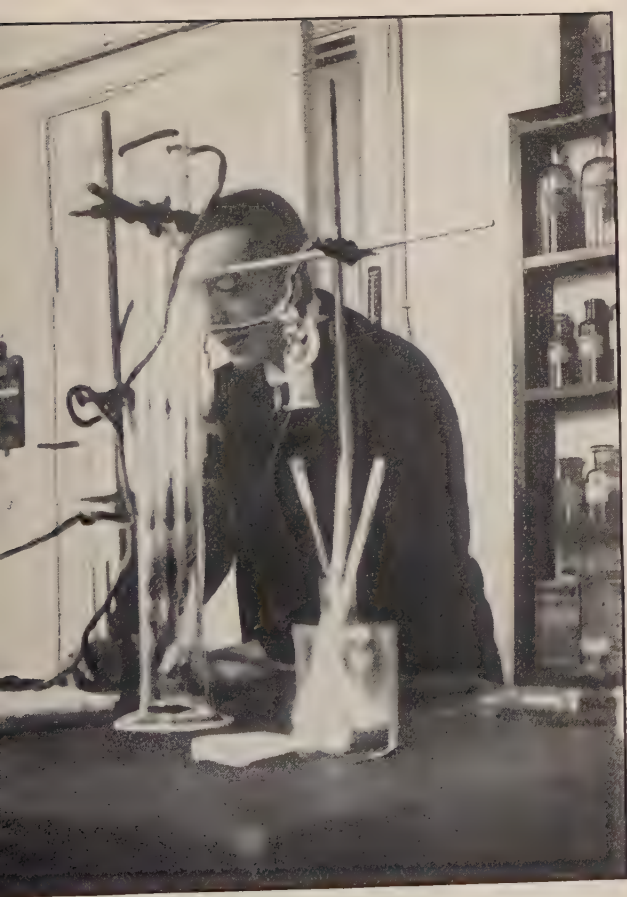


MENDELEEF, DISCOVERER OF THE PERIODIC LAW

Vol.—II.



SVANTE ARRHENIUS, CHEMIST AND COSMOLOGIST



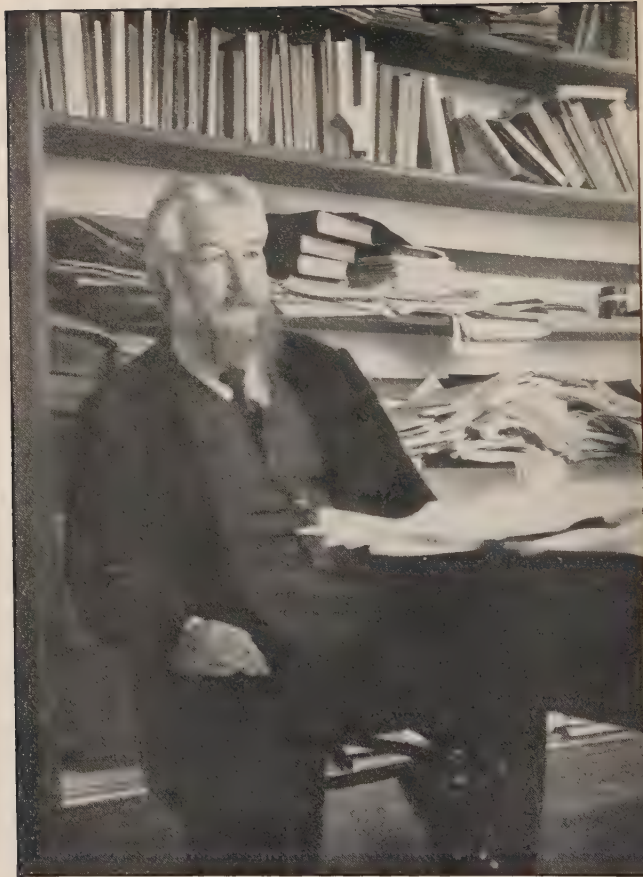
AN ELECTRO-CHEMICAL EXPERIMENT AT THE
NOBEL INSTITUTE



A LABORATORY OF EXPERIMENTAL CHEMISTRY



SEPARATING CHEMICALS BY DISTILLATION (LONG TUBE IN CENTER)



WILHELM OSTWOLD, CHEMIST AND PHILOSOPHER



J. HEINRICH VANT HOFF, DISCOVERER OF THE
LAW OF OSMOSIS



AN INDUSTRIAL LABORATORY (RESEARCH IN COMMERCIAL OILS)

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monovalent, while oxygen is divalent, makes it plain that we must expect to find no more than three compounds of these two elements, namely, $\text{H}-\text{O}-$ (written HO by the chemist, and called hydroxyl); $\text{H}-\text{O}-\text{H}$ (H_2O , or water), and $\text{H}-\text{O}-\text{O}-\text{H}$ (H_2O_2 , or hydrogen peroxid). It will be observed that in the first of these compounds the atom of oxygen stands, so to speak, with one of its hands free, eagerly reaching out, therefore, for another companion, and hence, in the language of chemistry, forming an unstable compound. Again, in the third compound, tho all hands are clasped, yet one pair links oxygen with oxygen; and this also must be an unstable union, since the avidity of an atom for its own kind is relatively weak.

Thus the well-known properties of hydrogen peroxid are explained, its easy decomposition, and the eagerness with which it seizes upon the elements of other compounds.

But the molecule of water, on the other hand, has its atoms arranged in a state of stable equilibrium, all their affinities being satisfied. Each hydrogen atom has satisfied its own affinity by clutching the oxygen atom; and the oxygen atom has both its bonds satisfied by clutching back at the two hydrogen atoms. Therefore the trio, linked in this close bond, have no tendency to reach out for any other companion, nor, indeed, any power to hold another should it thrust itself upon them. They form a "stable" compound, which under all ordinary circumstances will retain its identity as a molecule of water, even tho the physical mass of which it is a part changes

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its condition from a solid to a gas—from ice to vapor.

But a consideration of this condition of stable equilibrium in the molecule at once suggests a new question: How can an aggregation of atoms, having all their affinities satisfied, take any further part in chemical reactions? Seemingly such a molecule, whatever its physical properties, must be chemically inert, incapable of any atomic readjustments. And so in point of fact it is, so long as its component atoms cling to one another unremittingly. But this, it appears, is precisely what the atoms are not apt to do. It seems that they are fickle to the last degree in their individual attachments, and are as apt to break away from bondage as they are to enter into it. Thus the oxygen atom which has just flung itself into the circuit of two hydrogen atoms, the next moment flings itself free again and seeks new companions. It is for all the world like the incessant change of partners in a rollicking dance.

This incessant dissolution and reformation of molecules in a substance which as a whole remains apparently unchanged was first fully appreciated by Ste.-Claire Deville, and by him named dissociation. It is a process which goes on much more actively in some compounds than in others, and very much more actively under some physical conditions (such as increase of temperature) than under others. But apparently no substances at ordinary temperatures, and no temperature above the absolute zero, are absolutely free from its disturbing influence. Hence it is that molecules having all the valency of their atoms fully satisfied do not lose their chemical activity—since each

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atom is momentarily free in the exchange of partners, and may seize upon different atoms from its former partners, if those it prefers are at hand.

While, however, an appreciation of this ceaseless activity of the atom is essential to a proper understanding of its chemical efficiency, yet from another point of view the "saturated" molecule—that is, the molecule whose atoms have their valency all satisfied—may be thought of as a relatively fixed or stable organism. Even tho it may presently be torn down, it is for the time being a completed structure; and a consideration of the valency of its atoms gives the best clue that has hitherto been obtainable as to the character of its architecture. How important this matter of architecture of the molecule—of space relations of the atoms—may be was demonstrated as long ago as 1823, when Liebig and Wöhler proved, to the utter bewilderment of the chemical world, that two substances may have precisely the same chemical constitution—the same number and kind of atoms—and yet differ utterly in physical properties.

The word isomerism was coined by Berzelius to express this anomalous condition of things, which seemed to negative the most fundamental truths of chemistry. Naming the condition by no means explained it, but the fact was made clear that something besides the mere number and kind of atoms is important in the architecture of a molecule. It became certain that atoms are not thrown together haphazard to build a molecule, any more than bricks are thrown together at random to form a house.

How delicate may be the gradations of archi-

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tectural design in building a molecule was well illustrated about 1850, when Pasteur discovered that some carbon compounds—as certain sugars—can only be distinguished from one another, when in solution, by the fact of their twisting or polarizing a ray of light to the left or to the right, respectively. But no inkling of an explanation of these strange variations of molecular structure came until the discovery of the law of valency. Then much of the mystery was cleared away; for it was plain that since each atom in a molecule can hold to itself only a fixed number of other atoms, complex molecules must have their atoms linked in definite chains or groups. And it is equally plain that where the atoms are numerous, the exact plan of grouping may sometimes be susceptible of change without doing violence to the law of valency. It is in such cases that isomerism is observed to occur.

By paying constant heed to this matter of the affinities, chemists are able to make diagrammatic pictures of the plan of architecture of any molecule whose composition is known. In the simple molecule of water (H_2O), for example, the two hydrogen atoms must have released one another before they could join the oxygen, and the manner of linking must apparently be that represented in the graphic formula H—O—H . With molecules composed of a large number of atoms, such graphic representation of the scheme of linking is of course increasingly difficult, yet, with the affinities for a guide, it is always possible.

Of course no one supposes that such a formula, written in a single plane, can possibly represent the true architecture of the molecule: it is at best

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suggestive or diagrammatic rather than pictorial. Nevertheless, it affords hints as to the structure of the molecule such as the fathers of chemistry would not have thought it possible ever to attain.

PERIODICITY OF ATOMIC WEIGHTS

These utterly novel studies of molecular architecture may seem at first sight to take from the atom much of its former prestige as the all-important personage of the chemical world. Since so much depends upon the mere position of the atoms, it may appear that comparatively little depends upon the nature of the atoms themselves. But such a view is incorrect, for on closer consideration it will appear that at no time has the atom been seen to renounce its peculiar personality. Within certain limits the character of a molecule may be altered by changing the position of its atoms (just as different buildings may be constructed of the same bricks), but these limits are sharply defined, and it would be as impossible to exceed them as it would be to build a stone building with bricks. From first to last the brick remains a brick, whatever the style of architecture it helps to construct; it never becomes a stone. And just as closely does each atom retain its own peculiar properties, regardless of its surroundings.

Thus, for example, the carbon atom may take part in the formation at one time of a diamond, again of a piece of coal, and yet again of a particle of sugar, of wood fiber; of animal tissue, or of a gas in the atmosphere; but from first to last—from glass-cutting gem to intangible gas—there is no demonstrable change whatever in any single property of the atom itself. So far as we know,

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its size, its weight, its capacity for vibration or rotation, and its inherent affinities, remain absolutely unchanged throughout all these varying fortunes of position and association. And the same thing is true of every atom of all of the sixty-odd elementary substances with which the nineteenth century chemist was acquainted. Every one appears always to maintain its unique integrity, gaining nothing and losing nothing.

All this being true, it would seem as if the position of the Daltonian atom as a primordial bit of matter, indestructible and non-transmutable, had been put to the test by the chemistry of our century, and not found wanting. Since those early days of the century when the electric battery performed its miracles and seemingly reached its limitations in the hands of Davy, many new elementary substances have been discovered, but no single element has been displaced from its position as an undecomposable body. Rather have the analyses of the chemist seemed to make it more and more certain that all elementary atoms are in truth what John Herschel called them, "manufactured articles"—primordial, changeless, indestructible.

And yet, oddly enough, it has chanced that hand in hand with the experiments leading to such a goal have gone other experiments and speculations of exactly the opposite tenor. In each generation there have been chemists among the leaders of their science who have refused to admit that the so-called elements are really elements at all in any final sense, and who have sought eagerly for proof which might warrant their skepticism. The first bit of evidence tending to support this view was

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furnished by an English physician, Dr. William Prout, who in 1815 called attention to a curious relation to be observed between the atomic weight of the various elements. Accepting the figures given by the authorities of the time (notably Thomson and Berzelius), it appeared that a strikingly large proportion of the atomic weights were exact multiples of the weight of hydrogen, and that others differed so slightly that errors of observation might explain the discrepancy. Prout felt that this could not be accidental, and he could think of no tenable explanation, unless it be that the atoms of the various alleged elements are made up of different fixed numbers of hydrogen atoms. Could it be that the one true element—the one primal matter—is hydrogen, and that all other forms of matter are but compounds of this original substance?

Prout advanced this startling idea at first tentatively, in an anonymous publication; but afterwards he espoused it openly and urged its tenability. Coming just after Davy's dissociation of some supposed elements, the idea proved alluring, and for a time gained such popularity that chemists were disposed to round out the observed atomic weights of all elements into whole numbers. But presently renewed determinations of the atomic weights seemed to discountenance this practise, and Prout's alleged law fell into disrepute. It was revived, however, about 1840, by Dumas, whose great authority secured it a respectful hearing, and whose careful redetermination of the weight of carbon, making it exactly twelve times that of hydrogen, aided the cause.

Subsequently Stas, the pupil of Dumas, under-

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took a long series of determinations of atomic weights, with the expectation of confirming the Proutian hypothesis. But his results seemed to disprove the hypothesis, for the atomic weights of many elements differed from whole numbers by more, it was thought, than the limits of error of the experiments. It is noteworthy, however, that the confidence of Dumas was not shaken, tho he was led to modify the hypothesis, and, in accordance with previous suggestions of Clark and of Marignac, to recognize as the primordial element, not hydrogen itself, but an atom half the weight, or even one-fourth the weight, of that of hydrogen, of which primordial atom the hydrogen atom itself is compounded. But even in this modified form the hypothesis found great opposition from experimental observers.

In 1864, however, a novel relation between the weights of the elements and their other characteristics was called to the attention of chemists by Professor John A. R. Newlands, of London, who had noticed that if the elements are arranged serially in the numerical order of their atomic weights, there is a curious recurrence of similar properties at intervals of eight elements. This so-called "law of octaves" attracted little immediate attention, but the facts it connotes soon came under the observation of other chemists, notably of Professors Gustav Hinrichs in America, Dmitri Mendelèeff in Russia, and Lothar Meyer in Germany. Mendelèeff gave the discovery fullest expression, expositing it in 1869, under the title of "periodic law."

Tho this early exposition of what has since been admitted to be a most important discovery

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was very fully outlined, the generality of chemists gave it little heed till a decade or so later, when three new elements, gallium, scandium, and germanium, were discovered, which, on being analyzed, were quite unexpectedly found to fit into three gaps which Mendelèeff had left in his periodic scale. In effect, the periodic law had enabled Mendelèeff to predicate the existence of the new elements years before they were discovered. Surely a system that leads to such results is no mere vagary. So very soon the periodic law took its place as one of the most important generalizations of chemical science.

This law of periodicity was put forward as an expression of observed relations independent of hypothesis; but of course the theoretical bearings of these facts could not be overlooked. As Professor J. H. Gladstone has said, it forces upon us "the conviction that the elements are not separate bodies created without reference to one another, but that they have been originally fashioned, or have been built up, from one another, according to some general plan." It is but a short step from that proposition to the Proutian hypothesis.

NEW WEAPONS—SPECTROSCOPE AND CAMERA

But the atomic weights are not alone in suggesting the compound nature of the alleged elements. Evidence of a totally different kind has contributed to the same end, from a source that could hardly have been imagined when the Proutian hypothesis was formulated, through the addition of a novel weapon to the armamentarium of the chemist—the spectroscope.

The perfection of this instrument, in the hands

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of two German scientists, Gustav Robert Kirchhoff and Robert Wilhelm Bunsen, came about through the investigation, towards the middle of the century, of the meaning of the dark lines which had been observed in the solar spectrum by Fraunhofer as early as 1815, and by Wollaston a decade earlier. It was suspected by Stokes and by Fox Talbot in England, but first brought to demonstration by Kirchhoff and Bunsen, that these lines, which were known to occupy definite positions in the spectrum, are really indicative of particular elementary substances.

By means of the spectroscope, which is essentially a magnifying lens attached to a prism of glass, it is possible to locate the lines with great accuracy, and it was soon shown that here was a new means of chemical analysis of the most exquisite delicacy. It was found, for example, that the spectroscope would detect the presence of a quantity of sodium so infinitesimal as the one two-hundred-thousandth of a grain.

But what was even more important, the spectroscope put no limit upon the distance of location of the substance it tested, provided only that sufficient light came from it. The experiments it recorded might be performed in the sun, or in the most distant stars or nebulae; indeed, one of the earliest feats of the instrument was to wrench from the sun the secret of his chemical constitution.

To render the utility of the spectroscope complete, however, it was necessary to link with it another new chemical agency, namely, photography. This now familiar process is based on the property of light to decompose certain unstable compounds of silver, and thus alter their chemical

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composition. Davy and Wedgwood had barely escaped the discovery of the value of the photographic method. Their successors quite overlooked it until about 1826, when Louis J. M. Daguerre, the French chemist, took the matter in hand, and after many years of experimentation brought it to relative perfection in 1839, in which year the famous daugerreotype first brought the matter to popular attention. In the same year Mr. Fox Talbot read a paper on the subject before the Royal Society, and soon afterwards the efforts of Herschel and numerous other natural philosophers contributed to the advancement of the new method.

In 1843 Dr. John W. Draper, the famous English-American chemist and physiologist, showed that by photography the Fraunhofer lines in the solar spectrum might be mapped with absolute accuracy; also proving that the silvered film revealed many lines invisible to the unaided eye. The value of this method of observation was recognized at once, and, as soon as the spectroscope was perfected, the photographic method, in conjunction with its use, became invaluable to the chemist. By this means comparisons of spectra may be made with a degree of accuracy not otherwise obtainable; and in case of the stars, whole clusters of spectra may be placed on record at a single observation.

As the examination of the sun and stars proceeded, chemists were amazed or delighted, according to their various preconceptions, to witness the proof that many familiar terrestrial elements are to be found in the celestial bodies. But what perhaps surprized them most was to observe the

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enormous preponderance in the sidereal bodies of the element hydrogen. Not only are these vast quantities of this element in the sun's atmosphere, but some other suns appeared to show hydrogen lines almost exclusively in their spectra. Presently it appeared that the stars of which this is true are those white stars, such as Sirius, which had been conjectured to be the hottest; whereas stars that are only red-hot, like our sun, show also the vapors of many other elements, including iron and other metals.

In 1878 Mr. J. Norman Lockyer, in a paper before the Royal Society, called attention to the possible significance of this series of observations. He urged that the fact of the sun showing fewer elements than are observed here on the cool earth, while stars much hotter than the sun show chiefly one element, and that one hydrogen, the lightest of known elements, seemed to give color to the possibility that our alleged elements are really compounds, which at the temperature of the hottest stars may be decomposed into hydrogen, the latter "element" itself being also doubtless a compound, which might be resolved under yet more trying conditions.

We shall see in later chapters what science of the more recent period has to say about this aspect of the matter.

CHAPTER II

LOW TEMPERATURE RESEARCHES

IT seems distinctly odd that the Royal Institution of London should have been founded by an American. But such was the fact. The man who was born back in Colonial times as Benjamin Thompson and who became Count Rumford of the Holy Roman Empire was a most extraordinary person. At fourteen he was an unschooled grocer lad in a little New England village; at forty he was a world-famous savant, vice-president and medallist of the Royal Society, member of the most famous academies of Germany and France, a knight in Great Britain and a count in rank and more than half a king in power in Bavaria. But among all his titles to fame there was probably none that he cherished more deeply in his old age than the recollection of having founded the Royal Institution, the avowed purpose of which was the popular promulgation of useful knowledge and "the application of science to the common purposes of life."

Even while Rumford lived, the Royal Institution despite certain vicissitudes had attained great distinction through the work of Davy and Young; and in subsequent years its traditions were to be carried on by Faraday and Tyndall. The cumulative effect of the work of these men has made the Royal Institution perhaps the most famous of physical laboratories. Doubtless the present-day visitor to the Institution often ignores the name

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of its founder. But the name of this great American will always be linked in scientific annals with the names of Young, Davy, Faraday, and Tyndall. And it is worthy such association, for neither in native genius nor in realized accomplishments was Rumford inferior to these successors.

FROM LIQUID CHLORINE TO LIQUID HYDROGEN

Nor is it merely by mutual association with the history of the Royal Institution that these great names are linked. There was a curious and even more lasting bond between them in the character of their scientific discoveries. They were all pioneers in the study of those manifestations of molecular activity which we now, following Young himself, term energy. Thus Rumford, Davy, and Young stood almost alone among the prominent scientists of the world at the beginning of the past century in upholding the idea that heat is not a material substance—a chemical element—but merely a manifestation of the activities of particles of matter. Rumford's papers on this thesis, communicated to the Royal Society, were almost the first widely heralded claims for this then novel idea. Then Davy came forward in support of Rumford, with his famous experiment of melting ice by friction. It was perhaps this intellectual affinity that led Rumford to select Davy for the professorship at the Royal Institution, and thus in a sense to predetermine the character of the scientific work that should be accomplished there—the impulse which Davy himself received from Rumford being passed on to his pupil Faraday. There is, then, an intangible

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but none the less potent web of association between the scientific work of Rumford and some of the most important researches that were conducted at the Royal Institution long years after his death; and one is led to feel that it was not merely a coincidence that some of Faraday's most important labors should have served to place on a firm footing the thesis for which Rumford battled; and that Tyndall should have been the first in his "beautiful book" called *Heat, a Mode of Motion*, to give wide popular announcement to the fact that at last the scientific world had accepted the proposition which Rumford had vainly demonstrated three-quarters of a century before.

This same web of association extends just as clearly to the most important work which has been done at the Royal Institution in the present generation, and which is still being prosecuted there—the work, namely, of Professor James Dewar on the properties of matter at excessively low temperatures. Indeed, this work is in the clearest sense a direct continuation of researches which Davy and Faraday inaugurated in 1823 and which Faraday continued in 1844. In the former year Faraday, acting on a suggestion of Davy's, performed an experiment which resulted in the production of a "clear yellow oil" which was presently proved to be liquid chlorin. Now chlorin, in its pure state, had previously been known (except in a forgotten experiment of Northmore's) only as a gas. Its transmutation into liquid form was therefore regarded as a very startling phenomenon. But the clue thus gained, other gases were subjected to similar conditions by Davy, and particularly by Faraday, with the

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result that several of them, including sulphurous, carbonic, and hydrochloric acids were liquefied. The method employed, stated in familiar terms, was the application of cold and of pressure. The results went far towards justifying an extraordinary prediction made by that extraordinary man, John Dalton, as long ago as 1801, to the effect that by sufficient cooling and compressing all gases might be transformed into liquids—a conclusion to which Dalton had vaulted, with the sureness of supreme genius, from his famous studies of the properties of aqueous vapor.

Between Dalton's theoretical conclusion, however, and experimental demonstration there was a tremendous gap, which the means at the disposal of the scientific world in 1823 did not enable Davy and Faraday more than partially to bridge. A long list of gases, including the familiar oxygen, hydrogen, and nitrogen, resisted all their efforts utterly—notwithstanding the facility with which hydrogen and oxygen are liquefied when combined in the form of water-vapor, and the relative ease with which nitrogen and hydrogen, combined to form ammonia, could also be liquefied. Davy and Faraday were well satisfied of the truth of Dalton's proposition, but they saw the futility of further efforts to put it into effect until new means of producing, on the one hand, greater pressures, and, on the other, more extreme degrees of cold, should be practically available. So the experiments of 1823 were abandoned.

But in 1844 Faraday returned to them, armed now with new weapons, in the way of better air-pumps and colder freezing mixtures, which the labors of other workers, chiefly Thilorier, Mitch-

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ell, and Natterer, had made available. With these new means, and without the application of any principle other than the use of cold and pressure as before, Faraday now succeeded in reducing to the liquid form all the gases then known with the exception of six; while a large number of these substances were still further reduced, by the application of the extreme degrees of cold now attained, to the condition of solids. The six gases which still proved intractable, and which hence came to be spoken of as "permanent gases," were nitrous oxid, marsh gas, carbonic oxid, oxygen, nitrogen, and hydrogen.

These six refractory gases now became a target for the experiments of a host of workers in all parts of the world. The resources of mechanical ingenuity of the time were exhausted in the effort to produce low temperatures on the old hand and high pressures on the other. Thus Andrews, in England, using the bath of solid carbonic acid and ether which Thilorier had discovered, and which produces a degree of cold of -80° Centigrade, applied a pressure of five hundred atmospheres, or nearly four tons to the square inch, without producing any change of state. Natterer increased this pressure to two thousand seven hundred atmospheres, or twenty-one tons to the square inch, with the same negative results. The result of Andrews' experiments in particular was the final proof of what Cagniard de la Tour had early suspected and Faraday had firmly believed, that pressure alone, regardless of temperature, is not sufficient to reduce a gas to the liquid state. In other words, the fact of a so-called "critical temperature," varying for different substances,

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above which a given substance is always a gas, regardless of pressure, was definitively discovered. It became clear, then, that before the resistant gases would be liquefied means of reaching extremely low temperatures must be discovered. And for this, what was needed was not so much new principles as elaborate and costly machinery for the application of a principle long familiar—the principle, namely, that an evaporating liquid reduces the temperature of its immediate surroundings, including its own substance.

Ingenious means of applying this principle, in connection with the means previously employed, were developed independently by Pictet in Geneva and Cailletet in Paris, and a little later by the Cracow professors Wroblewski and Olzewski, also working independently. Pictet, working on a commercial scale, employed a series of liquefied gases to gain lower and lower temperatures by successive stages. Evaporating sulphurous acid liquefied carbonic acid, and this in evaporating brought oxygen under pressure to near its liquefaction point; and, the pressure being suddenly released (a method employed in Faraday's earliest experiments), the rapid expansion of the compressed oxygen liquefies a portion of its substance. This result was obtained in 1877 by Pictet and Cailletet almost simultaneously. Cailletet had also liquefied the newly discovered acetylene gas. Five years later Wroblewski liquefied marsh gas, and the following year nitrogen; while carbonic oxid and nitrous oxid yielded to Olzewski in 1884. Thus forty years of effort had been required to conquer five of Faraday's refractory gases, and the sixth, hydrogen, still remains re-

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sistant. Hydrogen had, indeed, been seen to assume the form of visible vapor, but it had not been reduced to the so-called static state—that is, the droplets had not been collected in an appreciable quantity, as water is collected in a cup. Until this should be done, the final problem of the liquefaction of hydrogen could not be regarded as satisfactorily solved.

More than another decade was required to make this final step in the completion of Faraday's work. And, oddly enough, yet very fittingly, it was reserved for Faraday's successor in the chair at the Royal Institution to effect this culmination. Since 1884 Professor Dewar's work has made the Royal Institution again the center of low-temperature research. By means of improved machinery and of ingenious devices for shielding the substance operated on from the accession of heat, to which reference will be made more in detail presently, Professor Dewar was able to liquefy the gas fluorin, recently isolated by Moussan, and the recently discovered gas helium in 1897. And in May, 1898, he was able to announce that hydrogen also had yielded, and for the first time in the history of science that elusive substance, hitherto "permanently" gaseous, was held as a tangible liquid in a cuplike receptacle; and this closing scene of the long struggle was enacted in the same laboratory in which Faraday performed the first liquefaction experiment with chlorin just three-quarters of a century before.

It must be noted, however, that this final stage in the liquefaction struggle was not effected through the use of the principle of evaporating liquids which has just been referred to, but by

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the application of a quite different principle and its elaboration into a perfectly novel method. This principle is the one established long ago by Joule and Thomson (Lord Kelvin), that compressed gases when allowed to expand freely are lowered in temperature. In this well-known principle the means was at hand greatly to simplify and improve the method of liquefaction of gases, only for a long time no one recognized the fact. Finally, however, the idea had occurred to two men almost simultaneously and quite independently. One of these was Professor Linde, the well-known German experimenter with refrigeration processes; the other, Dr. William Hampson, a young English physician. Each of these men conceived the idea—and ultimately elaborated it in practice—of accumulating the cooling effect of an expanding gas by allowing the expansion to take place through a small orifice into a chamber in which the coil containing the compressed gas was held. In Dr. Hampson's words:

"The method consists in directing all the gas immediately after its expansion over the coils which contain the compressed gas that is on its way to the expansion-point. The cold developed by expansion in the first expanded gas is thus communicated to the oncoming compressed gas, which consequently expands from, and therefore to, a lower temperature than the preceding portion. It communicates in the same way its own intensified cold to the succeeding portion of compressed gas, which, in its turn, is made colder, both before and after expansion, than any that had gone before. This intensification of cooling goes on until the expansion-temperature is far

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lower than it was at starting; and if the apparatus be well arranged the effect is so powerful that even the smaller amount of cooling due to the free expansion of gas through a throttle-valve, tho pronounced by Siemens and Coleman incapable of being utilized, may be made to liquefy air without using other refrigerants."

So well is this principle carried out in Dr. Hampson's apparatus for liquefying air that compressed air passing into the coil at ordinary temperature without other means of refrigeration begins to liquefy in about six minutes—a result that seems almost miraculous when it is understood that the essential mechanism by which this is brought about is contained in a cylinder only eighteen inches long and seven inches in diameter.

As has been said, it was by adopting this principle of self-intensive refrigeration that Professor Dewar was able to liquefy hydrogen. More recently the same result was attained through use of the same principle by Professor Ramsay and Dr. Travers at University College, London, who are to be credited also with first publishing a detailed account of the various stages of the process. It appears that the use of the self-intensification principle alone is not sufficient with hydrogen as it is with the less volatile gases, including air, for the reason that at all ordinary temperatures hydrogen does not cool in expanding, but actually becomes warmer. It is only after the compressed hydrogen has been cooled by immersion in refrigerating media of very low temperature that this gas becomes amenable to the law of cooling on expansion. In the apparatus used at University College the coil of compressed hydrogen is passed

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successively through (1) a jar containing alcohol and solid carbonic acid at a temperature of -80° Centigrade; (2) a chamber containing liquid air at atmospheric pressure, and (3) liquid air boiling in a vacuum bringing the temperature to perhaps -205° Centigrade before entering the Hampson coil, in which expansion and the self-intensive refrigeration lead to actual liquefaction. With this apparatus Dr. Travers succeeded in producing an abundant quantity of liquid hydrogen for use in the experiments on the new gases that were first discovered in the same laboratory through the experiments on liquid air—gases about which I shall have something more to say later.

PRINCIPLES AND EXPERIMENTS

At first blush it seems a very marvelous thing, this liquefaction of substances that under all ordinary conditions are gaseous. It is certainly a little startling to have a cup of clear, water-like liquid offered one, with the assurance that it is nothing but air; still more so to have the same air presented in the form of a white "avalanche snow." In a certain sense it is marvelous, because the mechanical difficulties that have been overcome in reducing the air to these unusual conditions are great. Yet, in another and broader view, there is nothing more wonderful about liquid air than about liquid water, or liquid mercury, or liquid iron. Long before air was actually liquefied, it was perfectly understood by men of science that under certain conditions it could be liquefied just as surely as water, mercury, iron, and every other substance could be brought to

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a similar state. This being known, and the principles involved understood, had there been nothing more involved than the bare effort to realize these conditions all the recent low-temperature work would have been mere scientific child's-play, and liquid air would be but a toy of science. But in point of fact there are many other things than this involved; new principles were being searched for and found in the course of the application of the old ones; new light was being thrown into many dark corners; new fields of research, some of them as yet barely entered, were being thrown open to the investigator; new applications of energy, of vast importance not merely in pure science but in commercial life as well, were being made available. That is why the low-temperature work must be regarded as one of the most important scientific accomplishments of our century.

At the very outset it was this work in large measure which gave the final answer to the long-mooted question as to the nature of heat, demonstrating the correctness of Count Rumford's view that heat is only a condition not itself a substance. Since about the middle of the century this view, known as the mechanical theory of heat, has been the constant guide of the physicists in all their experiments, and any one who would understand the low-temperature phenomena must keep this conception of the nature of heat clearly and constantly in mind. To understand the theory, one must think of all matter as composed of minute isolated particles or molecules, which are always in motion—vibrating, if you will. He must mentally magnify and visualize these particles till he sees them quivering before him, like tuning-

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forks held in the hand. Remember, then, that, like the tuning-fork, each molecule would, if left to itself, quiver less and less violently until it ran down altogether, but that the motion thus lessening is not really lost. It is sent out in the form of ether waves, which can set up like motion in any other particles which they reach, be they near or remote; or it is transmitted as a direct push—a kick, if you will—to any other particle with which the molecule comes in physical contact.

But note now, further, that our molecule, while incessantly giving out its energy of motion in ether waves and in direct pushes, is at the same time just as ceaselessly receiving motion from the ether waves made by other atoms, and by the return push of the molecules against which it pushes. In a word, then, every molecule of matter is at once a center for the distribution of motion (sending out impulses which affect, sooner or later, every other atom of matter in the universe), and, from the other point of view, also a center for the reception of motion from every direction and from every other particle of matter in the universe. Whether any given molecule will on the whole gain motion or lose it depends clearly on the simple mechanical principles of give and take.

From equally familiar mechanical principles, it is clear that our vibrating molecule, in virtue of its vibrations, is elastic, tending to be thrown back from every other molecule with which it comes in contact, just as a vibrating tuning-fork kicks itself away from anything it touches. And of course the vigor of the recoil will depend upon the vigor of the vibration and the previous move-

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ments. But since these movements constitute temperature, this is another way of saying that the higher the temperature of a body the more its molecules will tend to spring asunder, such separation in the aggregate constituting expansion of the mass as a whole. Thus the familiar fact of expansion of a body under increased temperature is explained.

But now, since all molecules are vibrating, and so tending to separate, it is clear that no unconfined mass of molecules would long remain in contiguity unless some counter influence tended to draw them together. Such a counter influence in fact exists, and is termed the "force" of cohesion. This force is a veritable gravitation influence, drawing every molecule towards every other molecule. Possibly it is identical with gravitation. It seems subject to some law of decreasing in power with the square of the distance; or, at any rate, it clearly becomes less potent as the distance through which it operates increases.

Now, between this force of cohesion which tends to draw the molecules together, and the heat vibrations which tend to throw the molecules farther asunder, there seems to be an incessant battle. If cohesion prevails, the molecules are held for the time into a relatively fixed system, which we term the solid state. If the two forces about balance each other, the molecules move among themselves more freely but maintain an average distance, and we term the condition the liquid state. But if the heat impulse preponderates, the molecules (unless restrained from without) fly farther and farther asunder, moving so actively that when they collide the recoil is too

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great to be checked by cohesion, and this condition we term the gaseous state.

After this explanation, it is clear that what the low-temperature worker does when he would liquefy a gas is to become the champion of the force of cohesion. He can not directly aid it, for so far as is known it is an unalterable quantity, like gravitation. But he can accomplish the same thing indirectly by weakening the power of the rival force. Thus, if he encloses a portion of gas in a cylinder and drives a piston down against it, he is virtually aiding cohesion by forcing the molecules closer together, so that the hold of cohesion, acting through a less distance, is stronger. What he accomplishes here is not all gain, however, for the bounding molecules, thus jammed together, come in collision with one another more and more frequently, and thus their average activity of vibration is increased and not diminished; in other words, the temperature of the gas has risen in virtue of the compression. Compression alone, then, will not avail to enable cohesion to win the battle.

But the physicist has another resource. He may place the cylinder of gas in a cold medium, so that the heat vibrations sent into it will be less vigorous than those it sends out. That is a blow the molecule cannot withstand. It is quite impotent to cease sending out the impulses however little comes in return; hence the aggregate motion becomes less and less active, until finally the molecule is moving so sluggishly that when it collides with its fellow cohesion is able to hold it there. Cohesion, then, has won the battle, and the gas has become a liquid.

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Such, stated in terms of the mechanical theory of heat, is what is brought to pass when a gas is liquefied in the laboratory of the physicist. It remains only to note that different chemical substances show the widest diversity as to the exact point of temperature at which this balance of the expansive and cohesive tendencies is affected, but that the point, under uniform conditions of pressure, is always the same for the same substance. This diversity has to do pretty clearly with the size of the individual molecules involved; but its exact explanation is not yet forthcoming, and, except in a general way, the physicist would not be able to predict the "critical temperature" of any new gas presented to him. But once this has been determined by experiment, he always knows just what to expect of any given substance. He knows, for example, that in a mixture of gases hydrogen would still remain gaseous after all the others had assumed the liquid state, and most of them the solid state as well.

These mechanical conceptions well in mind, it is clear that what the would-be liquefier of gases has all along sought to attain is merely the insulation of the portion of matter with which he worked against the access of heat-impulse from its environment. It is clear that were any texture known which would permit a heat-impulse to pass through it in one direction only, nothing more would be necessary than to place a portion of gas in such a receptacle of this substance, so faced as to permit egress but not entrance of the heat, and the gas thus enclosed, were it hydrogen itself, would very soon become liquid and solid, through spontaneous giving off of its energy, without any

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manipulation whatever. Contrariwise, were the faces of the receptacle reversed, a piece of iron placed within it would be made red-hot and melted though the receptacle were kept packed in salt and ice and no heat applied except such as came from this freezing mixture. One could cook a beefsteak with a cake of ice had he but such a material as this with which to make his stove. Not even Rumford or our modern Edward Atkinson ever dreamed of such economy of fuel as that.

But, unfortunately, no such substance as this is known, nor, indeed, any substance that will fully prevent the passage of heat-impulses in either direction. Hence one of the greatest tasks of the experimenters has been to find a receptacle that would insulate a cooled substance even partially from the incessant bombardment of heat-impulses from without. It is obvious that unless such an insulating receptacle could be provided none of the more resistant gases, such as oxygen, could be long kept liquid, even when once brought to that condition, since an environment of requisite frigidity could not practicably be provided.

But now another phase of the problem presents itself to the experimenter. Oxygen has assumed the quiescent liquid state, to be sure, but in so doing it has fallen below the temperature of its cooling medium; hence it is now receiving from that medium more energy of vibration than it gives, and unless this is prevented very soon its particles will again have power to kick themselves apart and resume the gaseous state. Something, then, must be done to insulate the liquefied gas, else it will retain the liquid state for too

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short a time to be much experimented with. How might such insulation be accomplished?

The most successful attack upon this important problem is that made by Professor Dewar. He invented a receptacle for holding liquefied gases which, while not fulfilling the ideal conditions referred to above, yet accomplishes a very remarkable degree of heat insulation. It consists of a glass vessel with double walls, the space between which is rendered a vacuum of the highest practicable degree. This vacuum, containing practically no particles of matter, can not, of course, convey heat-impulses to or from the matter in the receptacle with any degree of rapidity. Thus one of the two possible means of heat transfer is shut off and a degree of insulation afforded the liquefied substance. But of course the other channel, ether radiation, remains. Even this may be blocked to a large extent, however, by leaving a trace of mercury vapor in the vacuum space, which will be deposited as a fine mirror on the inner surface of the chamber. This mirror serves as an admirable reflector of the heat-rays that traverse the vacuum, sending more than half of them back again. The vacuum bottle thus devised is now in every-day use in our ordinary living. So, by the combined action of vacuum and mirror, the amount of heat that can penetrate to the interior of the receptacle is reduced to about one-thirtieth of what would enter an ordinary vessel. In other words, a quantity of liquefied gas which would evaporate in one minute from an ordinary vessel will last half an hour in one of Professor Dewar's best vacuum vessels. Thus in one of these vessels a quantity of lique-

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fied air, for example, can be kept for a considerable time in an atmosphere at ordinary temperature, and will only volatilize at the surface, like water under the same conditions, tho of course more rapidly; whereas the same liquid in an ordinary vessel would boil briskly away, like water over a fire. Only be it remembered, the air in "boiling" is at a temperature of about one hundred and eighty degrees below zero, so that it would instantly freeze almost any substance placed into it. A portion of alcohol poured on its surface will be changed quickly into a globule of ice, which will rattle about the sides of the vessel like a marble. That is not what one ordinarily thinks of as a "boiling" temperature.

If the vacuum vessel containing a liquefied gas be kept in a cold medium, and particularly if two vacuum tubes be placed together, so that no exposed surface of liquid remains, a portion of liquefied air, for example, may be kept almost indefinitely. Thus it becomes possible to utilize the liquefied gas for experimental investigation of the properties of matter at low temperatures that otherwise would be quite impracticable. Great numbers of such experiments have been performed in the past decade or so by all the workers with low temperatures already mentioned, and by various others, including, fittingly enough, the holder of the Rumford professorship of experimental physics at Harvard, Professor Trowbridge. The work of Professor Dewar has perhaps been the most comprehensive and varied, but the researches of Pictet, Wroblewski, and Olzewski have also been important, and it is not always possible to apportion credit for the various discoveries ac-

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curately, since the authorities themselves are in unfortunate disagreement in several questions of priority. But in any event, such questions of exact priority have no great interest for any one but the persons directly involved. We may quite disregard them here, confining attention to the results themselves, which are full of interest.

The questions investigated have to do with the physical properties, such as electrical conductivity, magnetic condition, light-absorption, cohesion, and chemical affinities of matter at excessively low temperatures. It is found that in all these regards most substances are profoundly modified when excessively cooled. Thus if a piece of any pure metal is placed in an electric circuit and plunged into liquid air, its resistance to the passage of the electricity steadily decreases as the metal cools, until at the temperature of the liquid it is very trifling indeed. The conclusion seems to be justified that if the metal could be still further cooled until it reached the theoretical "absolute zero," or absolutely heatless condition, the electrical resistance would also be nil. So it appears that the heat vibrations of the molecules of a pure metal interfere with the electrical current. The thought suggests itself that this may be because the ether waves set up by the vibrating molecules conflict with the ether strain which is regarded by some theorists as constituting the electrical "current." But this simple explanation falters before further experiments which show, paradoxically enough, that the electrical resistance of carbon exactly reverses what has just been said of pure metals, becoming greater and greater as the carbon is cooled. If an hypothesis were in-

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vented to cover this case there would still remain a puzzle in the fact that alloys of metals do not act at all like the pure metals themselves, the electrical resistance of such alloys being, for the most part, unaffected by changed temperature. On the whole, then, the facts of electrical conduction at low temperatures are quite beyond the reach of present explanation. They must await a fuller knowledge of molecular conditions in general than is at present available—a knowledge to which the low-temperature work itself seems one of the surest channels.

Even further beyond the reach of present explanation are the facts as to magnetic conditions at low temperatures. Even as to the facts themselves different experimenters have differed somewhat, but the final conclusion of Professor Dewar is that, after a period of fluctuation, the power of a magnet repeatedly subjected to a liquid-air bath becomes permanently increased. Various substances not markedly magnetic at ordinary temperatures become so when cooled. Among these, as Professor Dewar discovered, is liquid oxygen itself. Thus if a portion of liquid air be further cooled until it assumes a semi-solid condition, the oxygen may be drawn from the mass by a magnet, leaving a pure nitrogen jelly. These facts are curious enough, and full of suggestion, but like all other questions having to do with magnetism, they hold for the present generation the double fascination of insoluble mystery. To be sure, one may readily enough suggest that if magnetism be really a whirl in the ether, this whirl is apparently interfered with by the waves of radiant heat; or, again, that magnetism is presumably due to molecular

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motions which are apparently interfered with by another kind of molecular motions which we call heat vibrations; but there is a vagueness about the terms of such guesses that leaves them clearly within the category of explanations that do not explain.

When it comes to the phenomena of light, we can, as is fitting, see our way a little more clearly, since, thanks to Thomas Young and his successors, we know pretty definitely what light really is. So when we learn that many substances change their color utterly at low temperatures—red things becoming yellow and yellow things white, for example—we can step easily and surely to at least a partial explanation. We know that the color of any object depends simply upon the particular ether waves of the spectrum which that particular substance absorbs; and it does not seem anomalous that molecules packed close together at -180° of temperature should treat the ether waves differently than when relatively wide apart at an ordinary temperature. Yet, after all, that may not be the clue to the explanation. The packing of the molecules may have nothing to do with it. The real explanation may lie in the change of the ether waves sent out by the vibrating molecule; indeed, the fact that the waves of radiant heat and those of light differ only in amplitude lends color to this latter supposition. So the explanation of the changed color of the cooled substance is at best a dubious one.

Another interesting light phenomenon is found in the observed fact that very many substances become markedly phosphorescent at low temperatures. Thus, according to Professor Dewar,

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"gelatin, celluloid, paraffin, ivory, horn, and india-rubber become distinctly luminous, with a bluish or greenish phosphorescence, after cooling to -180° and being stimulated by the electric light." The same thing is true, in varying degrees, of alcohol, nitric acid, glycerin, and of paper, leather, linen, tortoise-shell, and sponge. Pure water is but slightly luminous, whereas impure water glows brightly. On the other hand, alcohol loses its phosphorescence when a trace of iodine is added to it. In general, colored things are but little phosphorescent. Thus the white of egg is very brilliant but the yolk much less so. Milk is much brighter than water, and such objects as a white flower, a feather, and egg-shell glow brilliantly. The most remarkable substances of all, says Professor Dewar, whom I am all along quoting, are "the platinocyanids among inorganic compounds and the ketonic compounds among organic. Ammonium platinocyanid, cooled while stimulated by arc light, glows fully at -180° ; but on warming it glows like a lamp. It seems clear," Professor Dewar adds, "that the substance at this low temperature must have acquired increased power of absorption, and it may be that at the same time the factor of molecular friction or damping may have diminished." The cautious terms in which this partial explanation is couched suggest how far we still are from a full understanding of the interesting phenomena of phosphorescence. That a molecule should be able to vibrate in such a way as to produce the short waves of light, dis severed from the usual linking with the vibrations represented by high temperature, is one of the standing puzzles of physics. And the demonstrated in-

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crease of this capacity at very low temperatures only adds to the mystery.

There are at least two of the low-temperature phenomena, however, that seem a little less puzzling—the facts, namely, that cohesion and rigidity of structure are increased when a substance is cooled and that chemical activity is very greatly reduced, in fact almost abolished. This is quite what one would expect *a priori*—tho no wise man would dwell on his expectation in advance of the experiments—since the whole question of liquids and solids *versus* gases appears to be simply a contest between cohesive forces that are tending to draw the molecules together and the heat vibration which is tending to throw them apart. As a substance changes from gas to liquid, and from liquid to solid, contracting meantime, simply through the lessening of the heat vibrations of its molecules, we might naturally expect that the solid would become more and more tenacious in structure as its molecules came closer and closer together, and at the same time became less and less active, as happens when the solid is further cooled. And for once experiment justifies the expectation. Professor Dewar found that the breaking stress of an iron wire is more than doubled when the wire is cooled to the temperature of liquid air, and all other metals are largely strengthened, tho none other to quite the same degree. He found that a spiral spring of fusible metal, which at ordinary temperature was quickly drawn out into a straight wire by a weight of one ounce, would, when cooled to -182° , support a weight of two pounds, and would vibrate like a steel spring so long as it was cool. A bell of fus-

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ible metal has a distinct metallic ring at this low temperature; and balls of iron, tin, lead, or ivory cooled to -182° and dropped from a height, "in all cases have the rebound greatly increased. The flattened surface of the lead is only one-third what it would be at ordinary temperature." "These conditions are due solely to the cooling, and persist only while the low temperature lasts."

If this increased strength and hardness of a contracted metal are what one would expect on molecular principles, the decreased chemical activity at low temperatures is no less natural-seeming, when one reflects how generally chemical phenomena are facilitated by the application of heat. In point of fact, it has been found that at the temperature of liquid hydrogen practically all chemical activity is abolished, the unruly fluorine making the only exception. The explanation hinges on the fact that every atom, of any kind, has power to unite with only a limited number of other atoms. When the "affinities" of an atom are satisfied, no more atoms can enter into the union unless some atoms already there be displaced. Such displacement takes place constantly, under ordinary conditions of temperature, because the vibrating atoms tend to throw themselves apart, and other atoms may spring in to take the places just vacated—such interchange, in fact, constituting the essence of chemical activity. But when the temperature is reduced the heat-vibration becomes insufficient to throw the atoms apart, hence any unions they chance to have made are permanent, so long as the low temperature is maintained. Thus it is that substances which attack one another eagerly at ordinary temperatures

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will lie side by side, utterly inert, at the temperature of liquid air.

Under certain conditions, however, most interesting chemical experiments have been made in which the liquefied gases, particularly oxygen, are utilized. Thus Olzewski found that a bit of wood lighted and thrust into liquid oxygen burns as it would in gaseous oxygen, and a red-hot iron wire thrust into the liquid burns and spreads sparks of iron. But more novel still was Dewar's experiment of inserting a small jet of ignited hydrogen into the vessel of liquid oxygen; for the jet continued to burn, forming water, of course, which was carried away as snow. The idea of a gas-jet burning within a liquid, and having snow for smoke, is not the least anomalous of the many strange conceptions that the low-temperature work has made familiar.

PRACTICAL RESULTS AND ANTICIPATIONS

Such are some of the strictly scientific results of the low-temperature work. But there are other results of a more directly practical kind—neither more important nor more interesting on that account, to be sure, but more directly appealing to the generality of the non-scientific public. Of these applications, the most patent and the first to be made available was the one forecast by Davy from the very first—namely, the use of liquefied gases in the refrigeration of foods. Long before the more resistant gases had been liquefied, the more manageable ones, such as ammonia and sulphurous acid, had been utilized on a commercial scale for refrigerating purposes. To-day every brewery and every large cold-storage warehouse

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is supplied with such a refrigerator plant, the temperature being thus regulated as is not otherwise practicable. Many large halls are cooled in a similar manner, and thus made comfortable in the summer. Ships carrying perishables have the safety of their cargoes insured by a refrigerator plant. In all large cities there are ice manufactories using the same method, and of late even relatively small establishments, hotels, and apartment houses have their ice-machine. It seems probable that before long all such buildings and many private dwellings will be provided with a cooling apparatus as regularly as they are now equipped with a heating apparatus.

The exact details of the various refrigerator machines of course vary, but all of them utilize the principles that the laboratory workers first established. Indeed, the entire refrigerator industry, now assuming significant proportions, may be said to be a direct outgrowth of that technical work which Davy and Faraday inaugurated and prosecuted at the Royal Institution—a result which would have been most gratifying to the founder of the institution could he have forecast it. The usual means of distributing the cooling fluids in the commercial plans is by the familiar iron pipes, not dissimilar in appearance (when not in operation) to the familiar gas, water, and steam pipes. When operating, however, the pipes themselves are soon hidden from view by the thick coating of frost which forms over them. In a moist beer-cellar this coating is often several inches in thickness, giving a very characteristic and unmistakable appearance.

Another commercial use to which refrigerator

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machines are now put is in the manufacture of various drugs, where absolute purity is desirable. As different substances congeal at different temperatures, but the same substances at uniform pressure always at the same temperature, a means is afforded of freeing a drug from impurities by freezing, where sometimes the same result cannot be accomplished with like thoroughness by any other practicable means. Indeed, by this means impurities have been detected where not previously suspected. And Professor Ramsay has detected some new elementary substances even, as constituents of the air, which had previously not been dissociated from the nitrogen with which they are usually mixed.

Such applications of the refrigerator principles as these, however, tho of vast commercial importance, are held by many enthusiasts to be but a bagatelle compared with other uses to which liquefied gases may some time be put. Their expectations are based upon the enormous potentialities that are demonstrably stored in even a tiny portion of, say, liquefied air. These are, indeed, truly appalling. Consider, for example, a portion of air at a temperature above its critical point, to which, as in Thilorier's experiments, a pressure of thirty-one tons to the square inch of the encompassing wall is being applied. Recall that action and reaction are equal, and it is apparent that the gas itself is pushing back—struggling against being compressed, if you will—with an equal power. Suppose the bulk of the gas is such that at this pressure it occupies a cubical space six inches on a side—something like the bulk of a child's toy balloon, let us say. Then the total

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outward pressure which that tiny bulk of gas exerts, in its desperate molecular struggle, is little less than five thousand tons. It would support an enormous building without budging a hair's-breadth. If the building weighed less than five thousand tons it would be lifted by the gas; if much less it would be thrown high into the air as the gas expanded. It gives one a new sense of the power of numbers to feel that infinitesimal atoms, merely by vibrating in unison, could accomplish such a result.

But now suppose our portion of gas, instead of being placed under our hypothetical building, is plunged into a cold medium, which will permit its heat-vibrations to exhaust themselves without being correspondingly restored. Then, presently, the temperature is lowered below the critical point, and, presto! the mad struggle ceases, the atoms lie amicably together, and the gas has become a liquid. What a transformed thing it is now. Instead of pressing out with that enormous force, it has voluntarily contracted as the five thousand tons pressure could not make it do; and it lies there now, limpid and harmless-seeming, in the receptacle, for all the world like so much water.

And, indeed, the comparison with water is more than superficial, for in a cup of water also there are wonderful potentialities, as every steam-engine attests. But an enormous difference, not in principle but in practical applications, exists in the fact that the potentialities of the water can not be utilized until relatively high temperatures are reached. Costly fuel must be burned and the heat applied to the water before it can avail to

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do its work. But suppose we were to place our portion of liquid air, limpid and water-like, in the cylinder of a locomotive, where the steam of water ordinarily enters. Then, tho no fuel were burned—tho the entire engine stood embedded in the snow of an arctic winter—it would be but a few moments before the liquid air would absorb even from this cold medium heat enough to bring it above its critical temperature; and, its atoms now dancing apart once more and re-exerting that enormous pressure, the piston of the engine would be driven back and then the entire cylinder burst into fragments as the gas sought exit.

In a word, then, a portion of liquid air has a store of potential energy which can be made kinetic merely by drawing upon the boundless and free supply of heat which is everywhere stored in the atmosphere we breathe and in every substance about us. The difficulty is, not to find fuel with which to vaporize it, as in case of water, but to keep the fuel from finding it whether or no. Were liquid air in sufficient quantities available, the fuel problem would cease to have any significance. But of course liquid air is not indefinitely available, and exactly here comes the difficulty with the calculations of many enthusiasts who hail liquefied gas as the motive power of the near future. For of course in liquefying the air power has been applied, for the moment wasted, and unless we can get out of the liquid more energy than we have applied to it, there is no economy of power in the transaction. Now the simplest study of the conditions, with the mechanical theory of matter in mind, makes it clear that this is precisely what one can never hope to

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accomplish. Action and reaction are equal and in opposite directions at all stages of the manipulation, and hence, under the most ideal conditions, we must expect to waste as much work in condensing a gas (in actual practice more) as the condensed substance can do in expanding to the original volume. Those enthusiasts who have thought otherwise, and who have been on the point of perfecting an apparatus which will readily and cheaply produce liquid air after the first portion is produced, are really but following the old perpetual-motion-machine will-o'-the-wisp.

It does not at all follow from this, however, that the energies of liquefied air may not be utilized with enormous advantage. It is not always the cheapest form of power-transformer that is the best for all purposes, as the use of the electrical storage battery shows. And so it is quite within the possibilities that a multitude of uses may be found for the employment of liquid air as a motive power, in which its condensed form, its transportability or other properties will give it precedence over steam or electricity. It has been suggested, for example, that liquefied gas would seem to afford the motive power par excellence for the flying-machine, once that elusive vehicle is well in harness, since one of the greatest problems here is to reduce the weight of the motor apparatus. In a less degree the same problem enters into the calculations of ships, particularly ships of war; and with them also it may come to pass that a store of liquid air (or other gas) may come to take the place of a far heavier store of coal. It is even within the possibilities that the explosive powers of the same liquid may take the

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place of the great magazines of powder now carried on war-ships; for, under certain conditions, the liquefied gas will expand with explosive suddenness and violence, an "explosion" being in any case only a very sudden expansion of a confined gas. And, indeed, the use of compressed air in many commercial fields already competing with steam and electricity is a step towards the use of air still further compressed, and cooled, meantime, to a condition of liquidity. The enormous advantages of the air actually liquefied, and so for the moment quiescent, over the air merely compressed, and hence requiring a powerful retort to hold it, are patent at a glance. But, on the other hand, the difficulty of keeping it liquid is a disadvantage that is equally patent. How the balance will be struck between these contending advantages and disadvantages it remains for the practical engineering inventors of the future—the near future, probably—to demonstrate.

Meantime there is another line of application of the ideas which the low-temperature work has brought into prominence which has a peculiar interest in the present connection because of its singularly Rumfordian cast, so to speak. I mean the idea of the insulation of cooled or heated objects in the ordinary affairs of life, as, for example, in cooking. The subject was a veritable hobby with the founder of the Royal Institution all his life. He studied the heat-transmitting and heat-reflecting properties of various substances, including such directly practical applications as rough surfaces *versus* smooth surfaces for stoves, the best color for clothing in summer and in winter, and the like. He promulgated his ideas far

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and wide, and demonstrated all over Europe the extreme wastefulness of current methods of using fuel. To a certain extent his ideas were adopted everywhere, yet on the whole the public proved singularly apathetic; and, especially in America, an astounding wastefulness in the use of fuel is the general custom now as it was a century ago. A French cook will prepare an entire dinner with a splinter of wood, a handful of charcoal, and a half-shovelful of coke, while the same fuel would barely suffice to kindle the fire in an American cook-stove. Even more wonderful is the German stove, with its great bulk of brick and mortar and its glazed tile surface, in which, by keeping the heat in the room instead of sending it up the chimney, a few bits of compressed coal do the work of a hodful.

It is one merit of the low-temperature work, I repeat, to have called attention to the possibilities of heat insulation in application to "the useful purposes of life." If Professor Dewar's vacuum vessel can reduce the heat-transmitting capacity of a vessel by almost ninety-seven per cent., why should not the same principle, in modified form, be applied to various household appliances—to ice-boxes, for example, and to cooking utensils, even to ovens and cook-stoves? Even in the construction of the walls of houses the principles of heat insulation might advantageously be given far more attention than is usual at present; and no doubt will be so soon as the European sense of economy shall be brought home to the people of the land of progress and inventions. The principles to be applied are already clearly to hand, thanks largely to the technical workers with low

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temperatures. It remains now for the practical inventors to make the "application to the useful purposes of life." The technical scientists, ignoring the example which Rumford and a few others have set, have usually no concern with such uninteresting concerns.

For the technical scientists themselves, however, the low-temperature field is still full of inviting possibilities of a strictly technical kind. The last gas has indeed been liquefied, but that by no means implies the last stage of discovery. With the successive conquest of this gas and of that, lower and lower levels of temperature have been reached, but the final goal still lies well beyond. This is the north pole of the physicist's world, the absolute zero of temperature—the point at which the heat-vibrations of matter are supposed to be absolutely stilled. Theoretically this point lies 272° below the Centigrade zero. With the liquefaction of hydrogen, a temperature of about -253° or -254° Centigrade has been reached. So the gap seems not so very great. But like the gap that separated Nansen from the geographical pole, it is a very hard road to travel. How to compass it will be the study of all the low-temperature explorers in the immediate future. Who will first reach it, and when, and how, are questions for the future to decide.

And when the goal is reached, what will be revealed? That is a question as full of fascination for the physicist as the north-pole mystery had been for the generality of mankind until Peary solved it. In the one case as in the other, attempts to answer partook largely of the nature of a guess, yet certain forecasts could be made

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with reasonable probability. Thus it can hardly be doubted that at the absolute zero all matter will have the form which we term solid; and, moreover, a degree of solidity, of tenacity and compactness greater than ever otherwise attained. All chemical activity will presumably have ceased, and any existing compound will retain unaltered its chemical composition so long as absolute zero pertains; tho in many, if not in all cases, the tangible properties of the substance—its color, for example, and perhaps its crystalline texture—will be so altered as to be no longer recognizable by ordinary standards, any more than one would ordinarily recognize a mass of snowlike crystals as air.

It has, indeed, been suggested that at absolute zero all matter may take the form of an impalpable powder, the forces of cohesion being destroyed with the vibrations of heat. But experiment seems to give no warrant to this forecast, since cohesion seems to increase exactly in proportion to the decrease of the heat-vibrations. The solidity of the meteorites which come to the earth out of the depths of space, where something approaching the zero temperature is supposed to prevail, also contradicts this assumption. Still less warrant is there for a visionary forecast at one time entertained that at absolute zero matter will utterly disappear. This idea was suggested by the observation, which first gave a clue to the existence of the absolute zero, that a gas at ordinary temperatures and at uniform pressure contracts by $\frac{1}{273}$ of its own bulk with each successive degree of lowered temperature. If this law held true for all temperatures, the gas would appar-

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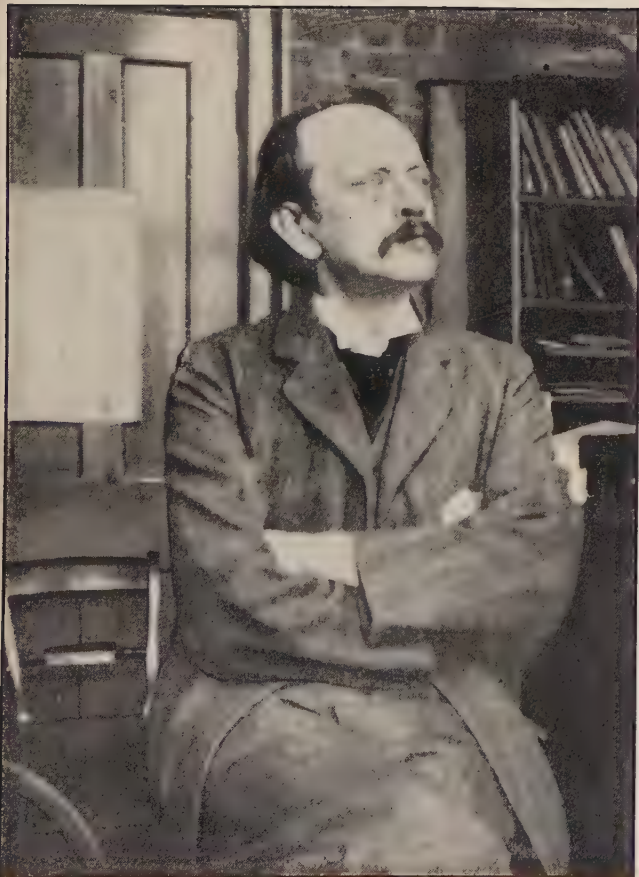
ently contract to nothingness when the last degree of temperature was reached, or at least to a bulk so insignificant that it would be inappreciable by standards of sense. But it was soon found by the low-temperature experimenters that the law does not hold exactly at extreme temperatures, nor does it apply at all to the rate of contraction which the substance shows after it assumes the liquid and solid conditions. So the conception of the disappearance of matter at zero falls quite to the ground.

But one can not answer with so much confidence the suggestion that at zero matter may take on properties hitherto quite unknown, and making it, perhaps, differ as much from the conventional solid as the solid differs from the liquid, or this from the gas. The form of vibration which produces the phenomena of temperature has, clearly, a determining share in the disposal of molecular relations which records itself to our senses as a condition of gaseousness, liquidity, or solidity; hence it would be rash to predict just what intermolecular relations may not become possible when the heat-vibration is altogether in abeyance. That certain other forms of activity may be able to assert themselves in unwonted measure seems clearly forecast in the phenomena of increased magnetism, and of phosphorescence at low temperatures above outlined. Whether still more novel phenomena may put in an appearance at the absolute zero, and if so, what may be their nature, are questions that must await the verdict of experiment. But the possibility that this may occur, together with the utter novelty of the entire subject, gives the low-temperature work precedence

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over almost every other subject now before the world for investigation (possible exceptions being radio activity and bacteriology). The quest of the geographical pole was but a child's pursuit compared with the quest of the absolute zero. In vital interest the one falls as far short of the other as the cold of frozen water falls short of the cold of frozen air.

Where, when, and by whom the absolute zero will be first reached are questions that may be answered from the most unexpected quarter. But it is interesting to know that great preparations are made in the laboratories of the Royal Institution for a further attack upon the problem. Already the research equipment there is the best in the world in this field, and recently this has been completely overhauled and still further perfected. It would not be strange, then, in view of past triumphs, if the final goal of the low-temperature workers should be first reached in the same laboratory where the outer territories of the unknown land were first penetrated three-quarters of a century ago. There would seem to be a poetic fitness in the trend of events should it so transpire. But of course poetic fitness does not always rule in the land of science.

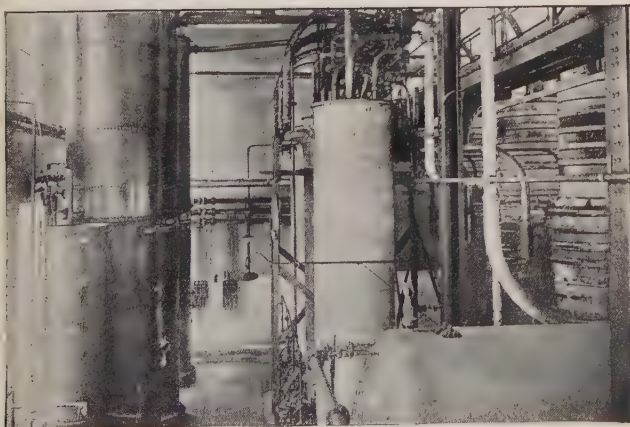


SIR J. J. THOMPSON, DISCOVERER OF THE ELECTRON

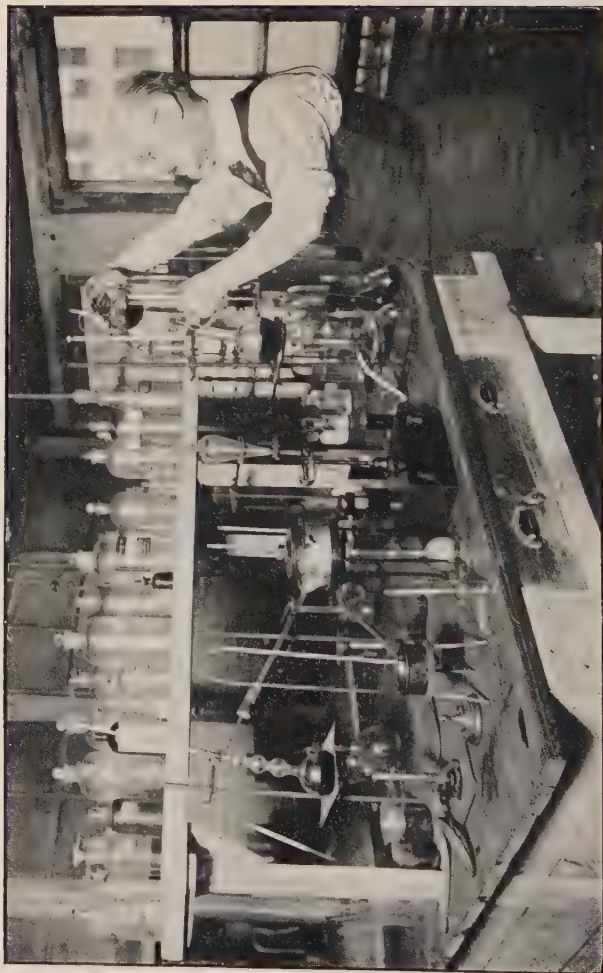
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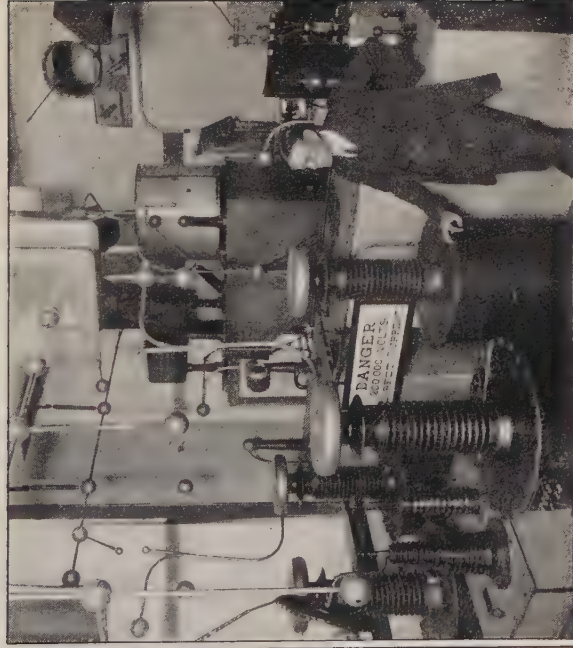
A SIMPLE BUT PRACTICAL LABORATORY



MIXING ROOM OF A CHEMICAL PLANT (ABOVE), AND
CONDENSERS AND PREHEATERS OF A BENZOL
RECOVERY PLANT

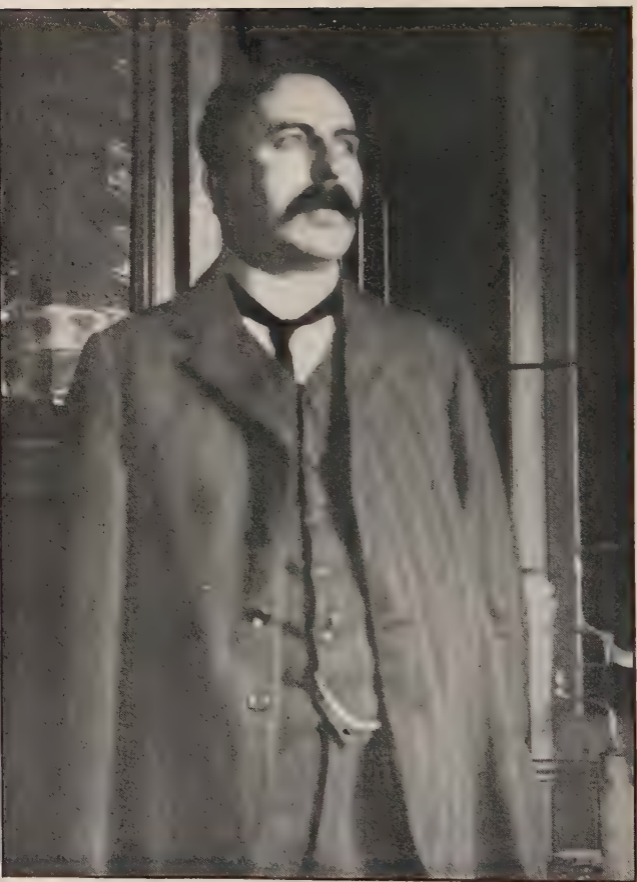


AN EXPERIMENT IN ORGANIC CHEMISTRY

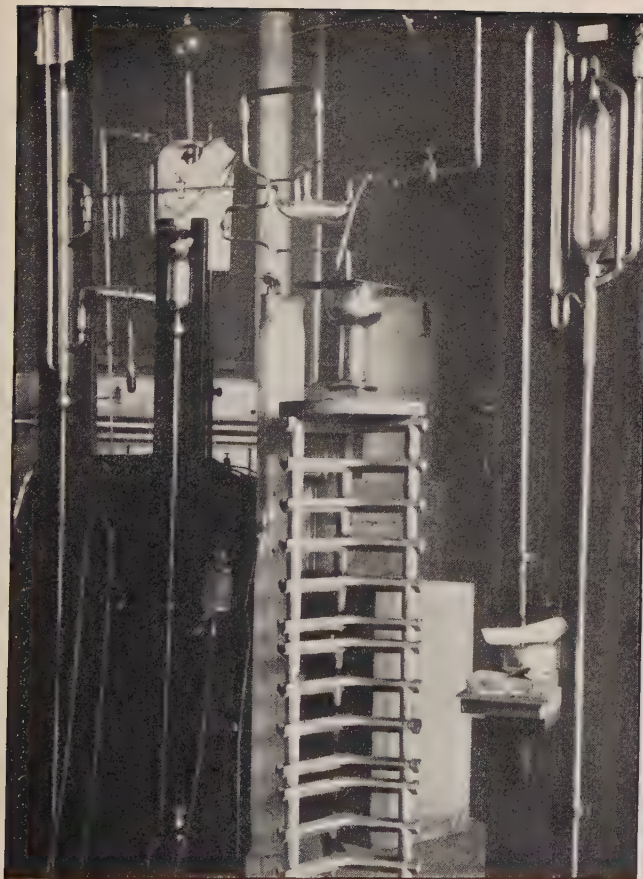


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A 200,000-VOLT X-RAY APPARATUS FOR MEDICAL USE (AT RIGHT), AND AN
X-RAY TREATMENT

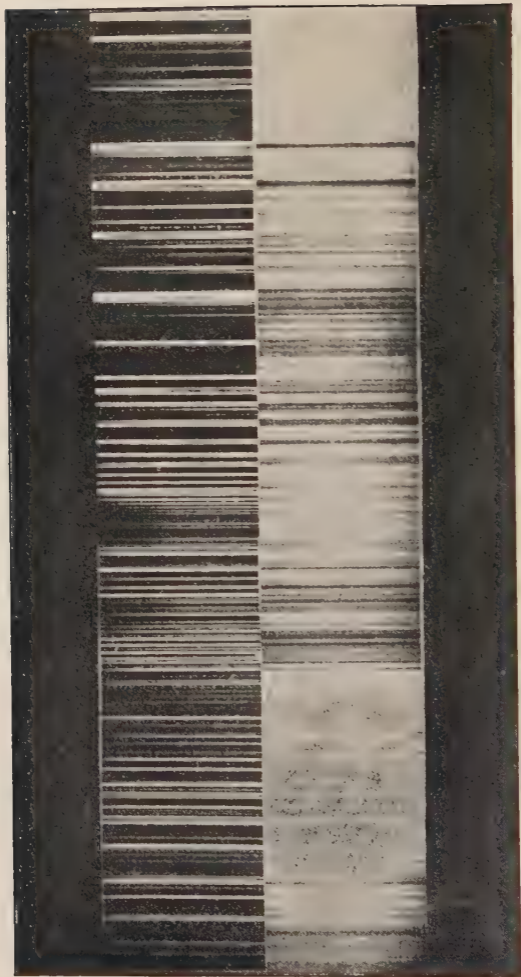


SIR ERNEST E. RUTHERFORD, FOREMOST OF
RADIUM EXPERTS



APPARATUS USED BY SIR ERNEST RUTHERFORD IN
STUDYING THE ALPHA PARTICLE

PHOTOGRAPHIC SPECTRA COMPARED



CHAPTER III

SVANTE ARRHENIUS AND THE NOBEL INSTITUTE OF SCIENCE

TO the average tourist, Stockholm seems a far-off corner of the world. Glancing at the map you find that it lies close to the sixtieth parallel,—on a level with Alaska and Central Hudson's Bay, and almost as far poleward as the southern point of Greenland. So there is a certain flavor of an arctic voyage—with a vague suggestion of ice floes, reindeer, and sledges—in the thought of going to the Swedish capital.

But in point of fact there is nothing of hardship involved in the journey. Indeed I know of no more comfortable twenty-two hours' trip anywhere in Europe or America than was afforded in the pre-war days by the Berlin-Stockholm express. You took the sleeper at Berlin at about eight in the evening and early next morning you found yourself traversing southern Sweden, the train having been carried across the seventy-five miles or so of water on a ferry boat of special construction. The sleeping car itself offered a degree of comfort that put our American Pullmans to the blush. The customs officers glanced at the outside of your luggage in the most perfunctory way; the guards were courteous to a degree; an excellent dining car was provided; and in general there was a pervading sense of comfort.

The all-day journey through Sweden was performed with few stops, and the landscape is suffi-

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ciently diversified to afford continual interest. Partly it is a low-lying, level country, curiously suggestive of the Mississippi Valley; the likeness being enhanced by the frame buildings that are markedly in contrast with the universal stucco edifices of the continent.

Farther north we enter the region of hills and pine forests, with boulders scattered everywhere, reminiscent of the glacial epoch. As we near Stockholm, the scattered boulders of the glacial moraine are no longer in evidence, but the out-cropping rocks everywhere are rounded and polished, telling of the masses of ice that once slowly ground their way across the region.

FARTHEST NORTH IN THE WORLD OF SCIENCE

It was early December when I made the trip, and the sun swung scarcely more than hand's breadth above the horizon at midday. By about three o'clock it had disappeared, but the afterglow lingered for more than an hour, and the sky was painted in the most miraculous colors, the view of which by itself would compensate one for a trip to the Northland.

After the long twilight had finally shaded into darkness, while there still remained a faint tint of amber toward the zenith, contrasting with the deep green of the horizon clouds, a crescent moon swung into view just above the silhouetted pine-clad hills, completing a scene that must remain among the ineffaceable pictures of memory.

Then shortly after six o'clock the train, precisely on time, drew into the commodious well-arranged station at Stockholm. A surprise—not to say shock—was in store when the official inter-

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preter who had answered our inquiries politely refused a fee; and another when at the hotel the porter from the station named the price for his services instead of depending upon the tourist's generosity,—his self-respecting method contrasting pleasantly with the continental custom.

But our glimpse of the brilliantly lighted streets of the city had revealed nothing to differentiate this from every other modern capital; the hotel clerk greeted us in excellent English; and half an hour later, in the dining-room, our acclimatization was made complete by the strains of Sousa's *Stars and Stripes* rendered by an excellent orchestra. So all dreams of an arctic experience vanished, and only the oddly spelled words on the menu card, and occasional bits of overheard conversation, remained to remind us that we were not spending the night in Berlin, Paris, or Naples,—or for that matter in London or New York.

I had come to Stockholm to see that lone scientific prophet of the Far North, Svante Arrhenius, officially the director of the Physical-Chemical Nobel Institute, but known to all the world as the founder of one of the most important hypotheses of to-day's chemical science, and as the most daring contemporary interpreter of the mysteries of cosmical physics;—a man who has worked and generalized in so many fields of science and to such good purpose that he has been not inaptly characterized as the Helmholtz of our generation.

Early next morning, following telephonic directions from the great chemist himself, I took a suburban trolley to a little station scarcely beyond the outskirts of the city of Stockholm, whence a

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short walk along a country road brought me to the Nobel Institute, and to the home of Arrhenius.

ARRHENIUS IN STUDY AND LABORATORY

The two buildings stand side by side, connected by a corridor, on a hill, in the midst of a grove of splendid oaks of a rugged type that seemed to typify the traditional character of the residents of the Northland. The buildings themselves are simple red brick structures, the residence not differing greatly in size or exterior appearance from the laboratory.

I found the famous chemist in his study, and was received with a cordiality that might have suggested the welcoming of an old friend rather than the introduction of a stranger,—illustrating again what my experience has so often and so forcibly called to mind, the fact that the greatest men among our contemporaries are the simplest in manner and the least ostentatious.

A generation has passed since Arrhenius first achieved universal fame in the world of science. Yet the Arrhenius that I met struck me as a man in the prime of life. He is rather short in stature and inclined to stoutness: the light brown hair is becoming scant above his dome-like forehead; but his complexion is florid, and his light blue eye has all the sparkling animation of youth. Every action reveals the man of vigor; of nervous temperament, if you will, but the kind of nervousness that betokens a tireless capacity for purposeful and productive action.

That Arrhenius has this capacity for work all who know him are agreed. It has been his custom from time to time to visit the laboratories of

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his confrères in the world of science and to sojourn there for a time and make experiments along lines aside from those of his own particular specialties. I recall that Professor Rutherford told me that Arrhenius once paid him a visit at Manchester and tried his hand at experimenting with radium emanation. He plunged into the work with customary ardor and soon felt himself to be on the track of a new discovery. So enthusiastic did he become that he remained at the laboratory until the very hour of departure of the train on which he planned to leave, and it became almost literally necessary to drag him away from his experiment that he might catch the train and keep an important engagement.

In his own laboratory Arrhenius works at all hours. "You see we are quite isolated here," he said, smiling, "and there is nothing to do but work." But I could readily judge from the temperament of the man that he would find "nothing to do but work" for a greater part of the time no matter what his surroundings. Nevertheless I was assured that he is fond of the social side of life; in other words, like most good workers, he can also be on occasion a good player after the day's work is done.

The Swedish meal hours differ somewhat from those of most countries of middle latitudes. Breakfast is served at 9:30, coffee at about 11:30, dinner at 4:30, and supper at 9:30. Arrhenius works before breakfast, and between meals throughout the day. The later evening he devotes to recreation.

As I glanced about the study in which we were sitting, I saw every evidence of the systematic

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worker. The books were neatly shelved, and there were only such papers on the flat-topped desk as were actually in use at the moment. I could understand the great amount and variety of work that Arrhenius has accomplished now that I saw something of his method. It was obvious that he has the gift not merely of attacking a subject with enthusiasm but of finishing his task,—which is doubtless one of the rarest endowments of productive genius. It is so easy to begin—so difficult to carry a task to completion.

It is interesting always to observe the portraits on the walls of a man's workshop. The most conspicuous picture on the wall of Arrhenius' study is a fine etching of the great Russian chemist, Mendelèeff, which its owner prizes not only because of its subject but because beneath it are the signatures of nearly all the famous contemporary chemists of the entire world. Another picture to which Arrhenius points with pride, is a little painting of the housekeeper of the great Swedish chemist, Berzelius,—a woman quite unknown to fame, but described as being a personage of real importance because of the devoted care she took of her master's interests. The other portraits include Berzelius, Arrhenius' father, Helmholtz, Kohlrausch, Linnhagen, the founder of the University of Stockholm, and Sir Joseph Thomson. In a neighboring room are two interesting paintings of Swedish scenes made by Professor Wilhelm Ostwald, and conspicuously placed in the entrance hall is a landscape by the youngest brother of the King of Sweden, who is an artist of real distinction, as this painting, to which

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Arrhenius points with particular pride, sufficiently attests.

A BRAND-NEW DISCOVERY

At the moment of my visit, Arrhenius was engaged in the preparation of an account of some brand-new experiments having to do with the absorption of gases.

"I am to deliver some important lectures next year," he said, "and of course I wish to have something new to say. Fortunately I have found something both new and valuable. Our experiments, just conducted here in the Institute, give an entirely new insight into the character of the absorption of gases by such a substance as, for example, charcoal.

"Hitherto it had been supposed that absorption might go on indefinitely, but we find that such is not the case. Moreover, the formula that applies to it is the same that applies to the compression of liquids. Beyond a certain degree of condensation, you cannot compress a liquid, no matter what the force applied. Similarly, beyond a certain limit there will be no further consumption of a gas by an absorbing medium."

Speaking with great animation, in perfectly fluent English, Arrhenius went on to detail the more technical bearings of this discovery; and I, listening, marveled at the freshness of view, the unflagging interest and enthusiasm that enabled this veteran worker to pursue his subject with the zeal of the neophyte. The spirit of the man had not changed since those college days when he astonished his teachers by the originality of his experiments and the audacity of his generalizations.

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A COLLEGE REMINISCENCE

The story of those early experiments of Arrhenius, with its spectacular sequel, came freely to my mind as I sat listening to the narrative of the new discovery. In imagination I could see the Arrhenius of 1884 pursuing his investigations at the University of Upsala with much the same fervidness of enthusiasm that characterizes his activities to-day. These earliest experiments, as all the world has since learned, had to do with the chemical and electrical activities of various solids when dissolved in water. Young Arrhenius reached the conclusion that when any solid is dissolved in water, some of its molecules are broken up into components bearing equivalent charges of negative and positive electricity, respectively.

When you drop a lump of ordinary table salt into a cup of water, for example, you are setting up an extraordinary electrical commotion. Particles of sodium conveying a unit charge of positive electricity dash off in one direction and particles of chlorin, conveying such a unit charge of negative electricity, in another. The more you dilute the solution, the greater the number of molecules that break up into these so-called electrical *ions*; and such obscure phenomena as osmotic pressure and the conduction of electricity through solutions are closely connected with and dependent upon this breaking-up or dissociation of molecules into their component ions.

All this seems familiar enough to-day; but it was a new doctrine when young Arrhenius propounded it in that doctorate thesis at the University of Upsala in 1884. To the professors who sat in judgment on the thesis it seemed a bizarre doc-

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trine, and some at least of them were apparently disposed to regard the thesis as giving inadequate evidence of the young applicant's fitness to receive a degree. It was finally decided, however, to accept the thesis, but with the lowest marking consistent with graduation. The faculty further showed their disapproval by declining to consider the young experimenter's application for a position as teacher in the University.

Now for the sequel. Just twenty years after the experiments were made that met with such scant recognition at the University at Upsala, the Nobel prize was given Arrhenius for these same experiments, which in the intervening period had been enlarged upon by multitudes of workers, and had come to be regarded as the foundation stones of a new and highly important structure of chemical theory. I reminded Arrhenius of this interesting bit of scientific history as we sat talking, and the smile with which he responded seemed to show that he recalled the incident quite without bitterness but with full appreciation of its humorous side.

THE NOBEL INSTITUTE

"Ah, that is a matter of long ago," he said; "let me show you my laboratories of to-day." And he led the way through the corridor into the Nobel Institute.

As we came to a window he pointed out the sites of the scientific institutions that will presently be grouped on the neighboring hills. These include a new zoological museum, and a botanical garden. The agricultural experiment station is already in operation near by. The Swedish Acad-

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emy of Science will have its seat in one of the new buildings. Altogether, then, this will be a notable group of scientific institutions with the Nobel Institute at its center. The ground belongs to the state and has been reserved for public institutions.

I need not describe in any detail the laboratories of the Nobel Institute, for one laboratory is much like another, and there is nothing in particular to distinguish, in the eye of the casual visitor, the laboratories of this institution from a thousand and one others, except the prime fact that Arrhenius is here. The building is a small one, suggesting a commodious residence rather than an institution, and there is room for only a few assistants, so that the entire work may be carried on under the close supervision of the director. There is a small but well-selected library, chiefly the property of Arrhenius himself; and the various workrooms, with their familiar equipment of crucibles, retorts, and electrical apparatus, are well lighted and admirably suited to their purpose.

But what struck me most forcibly about the equipment of the entire institution was its utter simplicity. As I ascended the pine stairs and noted everywhere the plain woodwork and the almost barren aspect of the rooms, I found it hard to realize that this is the material seat of a foundation whose prime function it is to give away five annual prizes of \$40,000 each. But the anomaly was explained to me by Arrhenius presently.

"You must understand," he said, "that the Nobel Institute, as such, is not rich. The original

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plan of the Foundation was to give away the entire income in the annual prizes, and the legatees have been able to set aside only a small percentage for the establishment and maintenance of these laboratories. So we could not indulge in extravagant furnishings if we wished. But again we should not care to do so if we could. The accomplishment of good work in science is not dependent upon the magnificence of one's surroundings."

REMINISCENCES OF NOBEL

After we had passed through the various laboratories of the institution, Arrhenius led me to a room where, in a sort of junk heap, numerous pieces of apparatus were stored that had been used by Alfred Nobel in the course of the experiments that led to the invention of dynamite and smokeless powder. As I viewed these interesting souvenirs, I was led to ask about the personality of Nobel himself.

He was not a scientific man, in the technical acceptance of the word, Arrhenius told me. That is to say, he was not trained in the methods of the chemical and physical laboratory. Yet he proved himself master of the scientific method, in that he accomplished results. Nitroglycerin when first compounded in 1847, by Sobrero, an Italian chemist, was considered as nothing more than a laboratory product, and its utilization as an explosive was entirely due to Nobel. Moreover, the application required an immense amount of experimentation, much of it of a most hazardous character. In 1867, for example, some four years after Nobel had taken out his first patents, his factory was

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destroyed by an explosion which cost the lives of his brother and an employee, and seriously injured his father.

So great seemed the danger in the handling of the new explosive, indeed, that strenuous efforts on Nobel's part were necessary to secure its introduction. After the explosion of 1867, the manufacture of nitroglycerin was forbidden in Stockholm, and Nobel was finally obliged to establish his laboratories on a raft in a river. Ultimately, however, he was able to prove that most of the accidents that resulted from the use of nitroglycerin were preventable, and the extreme utility of the explosive in blasting led to its early use by engineers and insured its ultimate acceptance.

THE ACCIDENTAL DISCOVERY OF DYNAMITE

One great difficulty connected with the use of nitroglycerin—or explosive oil as it was called—lay in its liquid character. Nobel's effort to incorporate it with ordinary gunpowder had not proved a success; nor did he find any other substance that would absorb it readily until quite by accident he spilled a quantity of the explosive on the floor of his laboratory, which chanced to be of a chalky earth composed largely—as is the case with all chalks—of the shells of minute aquatic organisms of an early geological period. Nobel noticed that this chalky earth absorbed the nitroglycerin; on making tests he found that a solid and portable explosive had been formed. In point of fact the accidental spilling of the nitroglycerin had performed a conclusive experiment and effected the

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invention of a new explosive superior in many ways to any hitherto produced. Nobel named the new explosive dynamite.

This was in 1867. Not long afterward the Franco-Prussian War gave opportunity for the practical demonstration of the destructive capacities of dynamite, and from that time its future was clearly assured. Nobel never ceased experimenting, however, and he finally invented a smokeless powder having almost as great significance in warfare as dynamite itself.

His most effective explosive was a modified dynamite, manufactured with the use of collodion, the discovery of which came about in a rather interesting way. Nobel had injured his finger, and he used collodion to make a protective film over the injured member. The wound proved painful, however, and being unable to sleep, Nobel arose at two in the morning and went to his laboratory. Having collodion at hand, the idea occurred to him to see the effect of combining this with nitroglycerin. The result was a pasty mass which he called gum-dynamite, and which has an explosive efficiency considerably greater than that of nitroglycerin itself.

The commercial success of Nobel's enterprise is sufficiently attested by the fortune he accumulated. Reduced to figures it may be of interest to record that the industries having to do with the production of explosive nitroglycerine compounds have an annual output of something like 125,000,000 pounds, representing a value of a quarter of a billion dollars, and giving employment to more than twelve thousand workers.

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NOBEL AS AN ADVOCATE OF PEACE

"But perhaps you are not aware," said Arrhenius, "that Nobel, tho his whole life was devoted to the manufacture of explosives, was an ardent advocate of universal peace."

"That surely sounds a trifle anomalous," I replied.

"Yet it is absolutely true. Nobel argued that the more terrible the means of destruction are made, the more will everyone hesitate to assume the responsibilities of declaring war. If you could make an explosive so destructive as certainly and completely to destroy both armies in a battle, all civilized nations would recoil in horror before the idea of war."

I recalled that Nobel's fellow-countryman, John Ericsson, builder of the *Monitor*, that prototype of all modern fighting ships, and of the torpedo destroyer, made similar claims for his instruments of destruction. Ericsson claimed that the principal aim of the torpedo destroyer was to make maritime warfare impossible and so to insure the neutrality of the seas. It is well known that Ericsson hoped that the art of war, thanks to ironclads and high explosives, might attain such perfection before the close of the nineteenth century as to force men to live in peace.

More cautious than his countrymen, Nobel did not attempt to predict the exact time when this consummation might be reached. He did express the belief, however, that the time may come when all civilized nations agree to unite forces in attacking any single nation that makes a declaration of war against any other nation—an advanced prediction of the League of Nations.

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But Nobel did not content himself with expressing the hope that an era of universal peace might ultimately come. Having accumulated an immense fortune through his inventions of destructive agencies, which all nations had adopted as part of their war-like equipment, he sought to utilize that fortune in promoting a fraternal spirit among the nations. This was his avowed object in bequeathing his entire fortune to the establishment of a fund, the interest of which should be used to give annual prizes for scientific and literary achievements, and for efforts specifically directed toward the abolition of war.

It may not be evident at first glance how the recognition of scientific and literary achievements is to promote the desired era of peace. But Nobel himself made this quite clear with a single pregnant sentence:

“Ignorance separates men; science unites them.”

The words embody a profound truth; and he who fully grasps their import will not doubt that the Nobel prizes for scientific achievement must be looked upon as important stepping stones toward the erection of that temple of universal brotherhood of which the founder dreamed.

NOBEL'S EXTRAORDINARY WILL

In commenting upon the personality of Nobel, Arrhenius called my attention to the amazing brief document which constituted the last will and testament of the great inventor, wherein he established the now famous Foundation.

When I examined this document, it seemed to me altogether extraordinary, and I was led to believe that it must have been devised by the

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inventor himself without the aid of legal advisers. Its simplicity, conciseness, and directness betoken the clear-thinking, practical man of affairs, while its aims and objects reveal the idealist. So markedly do the terse clauses of this document differ from the verbose and tortuous phraseology in which documents of a similar import are usually couched, that it seems worth while to quote it here in full. The entire text, then, of the portion of the will of Alfred Nobel, which under date of November 27, 1895, makes provision for the establishment of annual prizes, is as follows:

"The capital realized in values of all sorts by my executors shall become a fund of which the interest will be distributed every year to recompense those who, in the course of the current year, shall have been most useful to humanity.

"The sum shall be divided into five equal parts which shall be given:

"One part to the maker of the most important discovery or invention in physics;

"One part to the person who shall make the most important discovery or improvement in chemistry;

"One part to the maker of the most important discovery in physiology or medicine;

"One part to him who in literature shall have produced the work most remarkable in an ideal sense;

"One part to him who shall have worked most or best for the fraternization of peoples, and the suppression or diminution of permanent armies or for the formation and propagation of peace congresses."

In these few terse sentences provision is made

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for the distribution, as will appear, of five annual prizes. As the event proved, these prizes amount to about \$40,000 each, or a total of \$200,000 annually. The remaining sentences of the will merely name the executors, state in the fewest possible words that the prizes in physics and chemistry shall be awarded by the Swedish Academy of Science, the prize in physiology or medicine by the Carolin Institute of Stockholm, that for literature by the Academy of Stockholm, and that for peace by five members elected by the Norwegian Storting. A concluding sentence expresses the wish that national lines shall have no recognition in the distribution of the prizes.

The idea of utilizing a fortune for the betterment of humanity through this unique means was in itself a stroke of genius; the document in which the idea found expression may well be considered a literary triumph.

COSMOPOLITAN SCOPE OF THE NOBEL FOUNDATION

How fully the executors of the will have carried out the spirit and letter of the clause which provides that each prize shall be given to the most worthy performer, be he Scandinavian or not, will be understood when it is recorded that of the more than sixty distinguished scientific investigators who have received this blue ribbon of the scientific world—for such the annual Nobel diploma has come everywhere to be considered—only three have been countrymen of the founder. Twenty-three Germans have received the prize, and half as many Englishmen and Frenchmen. The list includes five Dutchmen, two Italians, a Spaniard, a Russian, three Danes, and even three

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Americans, Professor A. A. Michelson, of Chicago University, Dr. Alexis Carrel, of the Rockefeller Institute, and Professor T. W. Richards of Harvard. But in this cosmopolitan list there is, as I have said, the name of a Swede that was famous throughout the scientific world long before the Nobel prizes were founded. Needless to say I refer to Arrhenius.

It was inevitable that the Academy of Science of Sweden, with whom the decision rests, should select him as an early recipient of one of the annual Nobel prizes; tho, perhaps to emphasize their appreciation of the cosmopolitan spirit of the founder, they did not name their confrère until the third year. It was equally inevitable, when finally it was decided that the Nobel foundation should have a local habitation in an Institute of Science, that Arrhenius should be offered the directorship of this institution.

Hitherto professor of chemistry in the Stockholm University, and latterly rector of that institution, Arrhenius now transferred his activities to this new Nobel Laboratory. Here he entered on a new sphere of usefulness, under the most favorable conditions; conditions that fulfill his own expressed ideal of the complete divorcement of teaching from experiment.

ARRHENIUS THE GENERALIZER

It must not be supposed, however, that Arrhenius is likely to confine his activities to the mere field of experiment. Nothing could be more improbable than that. For the great investigator is after all preeminently a generalizer. As a mere experimenter, he is somewhat impatient of

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results. His mind leaps to conclusions, and the eagerness with which he attacks his subject is often but the evidence of his desire to test the truth of his preconceptions. The real greatness of his mind lies in his capacity to assimilate facts and weave them into systems.

It is familiar knowledge that there are thousands of workers capable of delving in laboratories and searching out new truths, where there is one man gifted with the powers of generalizing that can weave new facts and old into tenable hypotheses, preparing the way for further progress. Now and again, however, a man does appear who has at once the skill of the experimenter, the capacity to take in and mentally digest widely varied items of knowledge, and the creative imagination to correlate this knowledge.

Such a man is Svante Arrhenius. His earliest fame, as already pointed out, was won not merely by the novelty of his experiments but by the presentation of a new theory in explanation of the observed facts. His best known work of recent years has consisted of the marshaling of a wide array of more or less familiar facts in support of a unique theory that has singularly far-reaching implications. To this theoretical work we must now turn if we would gain a comprehensive view of the position occupied by the great Swede in the contemporary world of science.

The generalizations in question will carry us far afield from the realm of chemistry. They will take us from the microcosm of the test tube to the macrocosm of the universe, and bring to our attention such expansive subjects as star dust and nebulae, comets' tails and the aurora borealis, the

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activities of the myriad suns, the diffusion of living organisms among the planets, and the origin and destiny of the universe itself.

THE THEORY THAT SUNLIGHT EXERTS PRESSURE

The foundation idea lying back of the explanation of obscure cosmic phenomena with which the name of Arrhenius has been closely associated in recent years, is the assumption that the rays of sunlight exercise a pressure against any object upon which they impinge. It is familiarly known that the modern physicist regards light as consisting essentially of ether-waves of varying length, almost infinitely small, yet measurable by recognized laboratory methods. The longest visible waves give our eyes the impression of red; the shortest ones the impression of violet; and the intermediate colors of the spectrum are due to waves of intermediate lengths.

It is interesting to note that the celebrated mathematician Euler, who as long ago as 1746, contended for the wave theory of light expressed the opinion that these waves must exert a pressure upon any body against which they impinge. This contention naturally received scant notice from Euler's contemporaries, since they utterly disbelieved his theory of the nature of light; nor did the physicists of the early part of the nineteenth century give it much greater heed, altho, following the Englishman, Dr. Young, and the Frenchman, Fresnel, they came to accept the general validity of the wave theory.

In 1873, however, that most imaginative of English physicists, Clerk-Maxwell, in elaborating his treatise on the nature of electricity, showed

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that rays of heat must theoretically exert a pressure of a value calculable by the mathematician even if not, at that time, susceptible of instrumental measurement. Other calculations showed that a similar push must be given by ether-waves of every kind, including those that we interpret as light.

ARRHENIUS APPLIES THE THEORY

Yet another quarter century elapsed, however, before this hypothesis of light-pressure was brought conspicuously to the attention even of the scientific world. Then, in the year 1900, Arrhenius took it up, and attempted to show its vast importance for the explanation of sundry obscure celestial phenomena. His calculations showed that light pressure must constitute a highly important counter-force opposed to the universal force of gravitation. Particles of a certain degree of minuteness, he said, must be driven away from the sun or any other light-giving body, and thus distributed throughout the universe.

He calculated that the spherical particle of matter which would receive the strongest impulse from a ray of light, would be one of a diameter corresponding to the length of a light-wave. Such a sphere is so small that four hundred and seventy billion of them would be required to make up a cubic centimeter—let us say a large drop of water. Particles considerably larger than this would still have their weight more than compensated by the push of light-waves. But curiously enough, much smaller particles would not be affected by the light-waves, which in effect would pass round them, leaving them uninfluenced. And

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the existence of such smaller particles in infinite numbers is brought home to our imagination by the statement that each of the minute particles just referred to (those namely many billions of which are required to make a single drop of water) is made up in turn of no fewer than ninety-six million molecules.

Such figures convey to the average mind only the idea of almost infinite littleness; but they have much definiteness to the mind of the physicist, and they have a very practical application in the present connection. For example, they prove that matter in an actually gaseous condition will not be repelled from the sun by light-pressure, since a gas is made up of detached molecules and since a molecule is far too small to feel the influence of the waves of light.

In other words, the particles of matter that, according to the theory of Arrhenius are driven off from the sun by the impact of the waves of light, are of an appreciable, even tho microscopic size, vastly greater than the atoms and molecules with which the physicist is accustomed to deal. They are in short to be thought of rather as minute dust particles or droplets of water or condensed gases.

Arrhenius pointed out that the substance of the sun is in a constant state of turbulence; that its interior holds explosive compounds millions of times more powerful than dynamite, and that eruptions are constantly taking place which drive vast quantities of the sun's substance, pulverized and vaporized by explosion, out into space. The so-called corona or crown of light radiating from the sun is composed largely of eruptive matter.

It had been supposed hitherto that all the matter thus thrown out by the sun, even tho projected to a relatively vast distance, must presently be drawn back into the body of the sun by the influence of gravity. But according to the hypothesis now put forward by Arrhenius, a vast deal of this matter must be in exactly the state of fine subdivision that will render it subject to the influence of the light-rays, and will hence be driven off into space in straight lines, never to return.

THE TRUTH OF THE THEORY DEMONSTRATED

At the time when Arrhenius came forward with various striking applications of this thesis, the existence of light-pressure was, as already pointed out, a mere hypothesis. It appealed strongly to certain mathematicians, but the majority of physicists were doubtless disposed to regard it with distrust, notwithstanding the high authority of its champions.

But it chanced at the very moment when Arrhenius was attempting to apply the theory to the explanation of cosmical phenomena, some other workers were making experiments calculated to put the theory of light-pressure to the test of practical demonstration. Almost simultaneously, and quite independently, the Russian physicist, Lebedeff, and two Americans, Professor E. F. Nichols and G. F. Hull, performed experiments which conclusively demonstrated that the rays of light do exert precisely such a radiation pressure as had been predicated by the mathematicians; and, moreover, that the degree of pressure is

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precisely what Maxwell's calculations led him to designate.

The calculations of Maxwell and Arrhenius were, of course, of a character to be quite unintelligible to any one but the trained mathematician; but fortunately, the experiments of Professors Nichols and Hull were of a very tangible character, and such as to have a high degree of interest even for the layman.

One of these experiments was performed with the aid of a vacuum tube of hour-glass-like construction, and with dust composed partly of emery powder and partly of exceedingly minute pollen grains that had been charred and rendered porous by being heated to redness, so that they virtually constituted sponge-like particles of carbon. The object of thus calcining the pollen grains was to render them exceedingly light; and they had in point of fact a specific gravity—or weight relative to their size—only one-tenth that of water.

The dust, composed of emery particles and the spongy pollen grains, was allowed to run through the hour-glass aperture of the vacuum tube. A beam of light coming from an arc light and concentrated by a lens was projected against the stream of dust in the vacuum tube. This had no apparent effect upon the emery particles, but deflected the lighter particles of pollen so that they scattered across the tube in a filmy stream curiously suggestive of a comet's tail.

These minute particles of carbon had, in point of fact, been driven before the rays of light, precisely as Arrhenius supposed the particles of dust in the sun's atmosphere (and as we shall see in

a moment, other particles in the body of a comet) to be driven before the sun's rays.

This experiment (and others that need not be detailed here) set finally at rest all question as to the validity of the calculations upon which Arrhenius had based his new and sometimes startling explanations of celestial phenomena. Even for the scientific mind there is greater satisfaction in a visualized demonstration than in mere figures. So it is not strange that the theories of Arrhenius have received far more attention since the demonstration of light pressure was made, than even the high authority of their propounder could otherwise have gained for them. Arrhenius first gave expression to his views in his classical work on *Cosmical Physics*, published in German but never translated into English. More recently—in 1908—in a similar work of somewhat more popular character, he had elaborated and extended the theory by attempting to show that light-pressure plays a part in the mechanical system of the universe almost rivaling in universality the phenomena of gravitation itself.

COMETS' TAILS AND THE AURORA BOREALIS EXPLAINED

One of the earliest applications of the theory of light-pressure dealt with the old problem of the origin and nature of that familiarly observed yet obscure phenomenon, the comet's tail.

The previously current explanation had interpreted the curious film which projects from the body of the comet as due to electrical influence. Arrhenius was disposed to admit that electricity enters into the case, since light and heat would

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act on the gaseous matter of the comet's body in such a way as to ionize its particles,—that is to say separate them into two groups, one charged with negative, the other with positive, electricity.

It is known that negatively charged ions tend to become centers of condensation for watery vapor. Arrhenius supposes that clouds of particles are thus formed in the cometary body of an appropriate size to come under the influence of the pressure of the light-rays. His calculations show that particles of precisely the right size may receive from the waves of light a push forty times more powerful than the gravitation pull which the sun exerts on the same particles. Such particles would obviously be driven off at a high rate of speed from the comet's body in the direction away from the sun. Other particles of somewhat larger size would receive a less preponderant push, so that the various observed types of comets' tails are clearly accounted for.

Meantime, the main substance of the comet is composed of particles so large that the gravitation exerted on them vastly outmatches the radiation pressure; or, on the other hand, of gaseous molecules so small as to elude the light-waves; so that the main substance of the comet holds to an orbit determined by the laws of gravitation in defiance of the counteracting influence of the light-waves.

In the same way, Arrhenius conceives the formation in the atmosphere of the sun itself of vast quantities of particles charged with electricity, which are driven off into space by the light-pressure. As these particles of charged dust are conceived to be streaming incessantly in all directions,

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they of course are projected constantly into the earth's atmosphere.

Here, according to the theory of Arrhenius, the negatively charged particles come under the influence of the earth's lines of magnetic force and hence are directed toward the magnetic poles. The familiar but never adequately explained phenomena of the aurora borealis are due, so he believes, to the polar concentration of large quantities of negatively charged dust that has thus come to us from the sun.

The less familiar phenomena of the zodiacal light—a great fan-shaped beam light visible chiefly in tropical regions after twilight—he ascribes to the same source. The seemingly angular form of the beam of light, he explains as a perspective effect, the particles themselves being directed in virtually parallel lines from or toward the sun.

NEW LIGHT ON METEORS AND NEBULÆ

It is an obvious consequence of the theory of light-pressure, as thus expounded by Arrhenius, that all space is supposed to be permeated with particles of dust thus driven out from each of the myriads of suns that we term stars. As the particles of matter thus radiating in every direction would necessarily come more or less into collision, the formation of those masses of world-stuff which are known to us as meteors would be accounted for. Our earth receives annually a mass of meteoric dust variously estimated at from 20,000 to 200,000 tons. No antecedent theory gave plausible explanation of the existence in space of

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such vast quantities of isolated fragments of world-stuff.

In the view of the astronomers, comets are only aggregations of meteors; and some at least of those interesting solar bodies the nebulae, which exist in such vast numbers throughout the universe, are in effect only gigantic comets. According to this view, then, nebulae would be in perpetual process of re-formation, constantly receiving accretions from the particles of matter thrown out by the active suns. They thus serve as repositories not only of matter but of energy, and, so Arrhenius believes, they constitute the celestial mechanisms by which the universe is prevented from settling finally into the condition of a run-down clock, or of a worn-out machine.

But again, nebulae are, according to current astronomical notions, themselves the basal matter, so to speak, out of which new suns are developed through condensation. So the influence of light-pressure, which must be thought of as thus perpetually scattering particles of matter through the universe, as linked with the opposing influence of gravitation in the great cyclic process of world-making and world destruction.

Add that suns that have finally burned out and ceased to give light will ultimately be rejuvenated, so to say, by impact with other suns, thereby forming incandescent masses that will presently cool into new solar systems, and we have a picture of the life history of celestial bodies wherein, to quote the words of Arrhenius, "the cycle transition from the nebular to the star stage and vice versa, will occur in a regular rhythm during the

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immeasurable epochs which we must concede for the evolution of the universe.

"By virtue of this compensating cooperation of gravity and the radiation pressure of light, as well as of temperature and heat concentration," so Arrhenius believes, "the evolution of the worlds can continue in an eternal cycle, in which there is neither beginning nor end, and in which life may exist and continue forever and undiminished."

LIFE IN OTHER WORLDS

The concluding clause of the sentence just quoted requires a few words of explanation. When Arrhenius says that "life may continue forever and undiminished" he does not refer to life on our planet or any other individual planet. In common with other students he conceives that our sun must ultimately become cold (tho he optimistically extends the terms of its possible life to hundreds of millions or even billions of years), and hence he cannot avoid the conclusion that life must ultimately be blotted out on the earth. But he conceives that there are endless numbers of other planets inhabited by living organisms more or less similar to those that inhabit the earth. And he again invokes the waves of light as the medium through which the germs of living organisms are distributed throughout the universe and as it were sown from one planet to another.

I shall outline this hypothesis only in the briefest terms; partly because of limitations of space, partly because I do not personally attach to this part of the great Swedish generalizer's hypothesis an importance commensurate with its other features. To me it seems far more probable that

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living organisms originate *de novo* on each successive planet that becomes fitted to their habitation, than that the germs of life are transported across the vast spaces that separate the multitudinous solar systems. But this personal opinion does not prevent me from fully appreciating the unique and interesting character of Arrhenius' suggestion, which, in any event, must be treated with respect—if for no other reason—because it has his sanction.

Briefly, then, the idea as Arrhenius outlines it is this. Bacterial spores of a size not far removed from that of those particles which are proved to be subject to the influence of the light-rays are known to exist and to float constantly in the air. Convection currents must carry these spores on occasion into the upper atmosphere. Here they may become electrified and projected into space until finally they are so loosely held by the earth's gravitation pull that the waves of sunlight can, as it were, take them in tow.

Arrhenius calculates that a spore thus driven by the rays of light would cross the orbit of Mars after twenty days. It would pass the orbit of Jupiter after eight days, and the far outlying orbit of Neptune after fourteen months. Passing on at the same speed, the migrating spore would require nine thousand years to reach the nearest star, on some attendant planet of which it might be deposited. During transit the temperature of the spore would be reduced to about -220° C.

CAN LIFE COME TO US FROM THE STARS?

At first glance this mere statement of the elements of time and temperature may seem to re-

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duce the theory to an absurdity. But Arrhenius points out that organisms have been proved in the laboratory to be able to withstand the influence of the temperature of liquid hydrogen for many hours without being destroyed. He estimates that the vital functions of lower organisms are reduced in such ratio by low temperatures, that, to quote his own words, "the germinating power of spores at -220 degrees would not be diminished during the period of three million years to any greater degree than during one day at a temperature of 10 degrees."

In this, and in similar estimates through which Arrhenius fortifies his theory, free scope is evidently being given to speculation, but we must recall that the great generalizer everywhere supports his views with suggestive figures and corroborative experiments. He freely admits, of course, that there is little probability that we shall ever be able to demonstrate the correctness or falsity of his main contention, since even if a germ spore from another world were actually to be observed through the microscope, there would be no way of proving its extra-mundane origin. On the other hand, it seems futile to deny the possibility of such an occurrence, and assuredly that possibility must add a touch of new interest to the always alluring explorations of the bacteriologist.

It should stir the imagination of the most prosaic microscopist to reflect that the infinitesimal spore revealed by his lens may be a visitor not merely from our next-door neighbor Mars, but from some unknown stellar system so far removed that the tiny emigrant, voyaging elf-like on its

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sunbeam, has required thousands of years to make the journey across the intervening ocean of ether.

Should the idea seem fantastic, let it not be forgotten that it records the sober thought of a man who through years of rigid experimental work in the laboratory has earned the right to theorize, and whose fame is such that his every pronouncement is assured a respectful hearing in the most restricted and aristocratic circles of the scientific world.

CHAPTER IV

WILHELM OSTWALD AND THE NEW CHEMISTRY

HERR Geheimrat Hofrat Professor Doctor Wilhelm Ostwald." That is the way he is named in a letter from an official German source, that lies before me. The phrase sounds strange to American ears. But the titles have significance and meaning, and I quote them here not without purpose. I wish to note that they were not conferred for any political achievement, but purely and simply because of Professor Ostwald's attainments in the field of natural science. There is a significance about this custom of honoring those whose intellectual efforts brought fame to the pre-war Fatherland to which I shall refer before I am through.

Meantime our concern is with Geheimrat Ostwald himself, who, titles aside, is one of the most remarkable educators of his generation. His laboratories at Leipzig were for many years the most important centers for chemical education in Germany, and his extraordinary capacities as lecturer and writer have extended his influence far beyond the bounds of the University.

I first met Professor Ostwald in Berlin in the pre-war days, where he had come to deliver a lecture before a philosophical society. I had a chat with him in the evening and we breakfasted together next morning, and the glimpses of a highly interesting personality that were at once

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revealed led me to accept with alacrity the invitation to pay him a visit at his home. I knew that he had left the university work two or three years before, and established himself in a country place at a little town called Grossbothen. I shall have more to say of this idyllic retreat in a moment, but first I must speak of the personality of Professor Ostwald himself.

In physique and general aspect the great chemist might be described as typically German. He is rather above medium stature; of distinctly robust build, with fair, ruddy complexion, light blue eyes, and hair and beard that are touched with gray. In general appearance as well as in frankness of manner and freedom of expression, Professor Ostwald reminded me of Professor Haeckel; a resemblance which the great chemist himself explained on the ground that they are both typical Germans.

I may add that I learned with surprise that these two eminent scientific workers and thinkers, who spent the major part of their lives less than fifty miles apart—one in Leipzig, the other in Jena—had never met, tho they occasionally corresponded or exchanged books. I was interested, too, to note that, as evidencing the rapid progress of our age, Professor Ostwald regarded Haeckel as belonging to an elder generation and to an almost obsolescent epoch of thought. Yet Haeckel was only twenty years the elder.

Professor Ostwald himself, at the time of this visit, was in his fifty-eighth year, and hence, according to his own favorite theory, he had passed the period when important scientific discoveries could be expected of him, unless he were to enter

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some field to him entirely new. "We must look to the young men for important new discoveries," he declared. "After one has worked a certain number of years along any given line, the creative capacities of his mind seem to have become literally exhausted. Hence we find that most great scientific investigators perform their really useful work before middle age, their later years ceasing to be productive."

"What about a man like Helmholtz?" I suggested.

"His case is exceptional chiefly because he turned to new fields of science. He was at one time mathematician, at another physicist, at yet another physiologist. Having as it were exhausted one compartment of his brain he opened up another compartment. That, I believe, is possible for every man of genius; indeed, it is precisely by such shifting of the point of view that a constructive mind may continue its usefulness into middle life and for that matter even in old age."

Elaborating this idea, which has obvious interest and importance, Professor Ostwald declared that in his judgment we were entering upon an era in which the specialist in science, as in other fields, will no longer be as dominant as he has been in recent years. "A man must be a specialist in the beginning, of course," he said. "That constitutes a necessary preparation. Yet the real importance of special work is that it provides material for the generalizer. An array of technical facts constitutes after all only the brick and mortar. Philosophical interpretation of these

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facts is all essential to the erection of the complete structure."

I was led from this and sundry similar remarks that occurred in the course of our conversations to see that Professor Ostwald is applying his philosophy of life to his personal activities. Having devoted many arduous years to laboratory experiments, he now conceived that his most useful work must lie along the lines of philosophical interpretation. He was attempting to apply his vast fund of technical knowledge to the interpretation of social and economic phenomena. In other words, being a true and typical German, he could not escape the traditional racial propensity to philosophize. Famous for a generation as a great chemical worker and teacher, he was now achieving new fame as a philosopher. And he came to his new task with a display of interest, energy, and enthusiasm, and with a freshness of viewpoint which we are wont to think of as typifying youth rather than middle age; which, rather let us say, are the marks of genius regardless of age; the signs and symbols of the progressive, creative, exceptional intellect.

MY VISIT TO GROSSBOTHEN

The environment selected by Professor Ostwald as the seat of his latter-day activity had for me peculiar interest. Grossbothen-bei-Leipzig, as it is officially cataloged, is a small town situated, as the name implies, not many miles from Leipzig. It consists chiefly of two rows of houses flanking a long street,—so drawn out and tenuous a town, if the phrase be permitted, that one felt oneself quite in the country, even when in the heart of the

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village. In the main the houses have not even the influence of age to give them picturesqueness. They are stucco structures with tiled roofs, distinctly modern in aspect.

Yet the flavor of medievalism pervaded the place. When our train drew into the station the only persons to alight were half a score of aged women, each with a large basket strapped on her back, and these quaint, witch-like figures, scurrying along the road and disappearing down the street, left the place deserted save for the station master and a lone teamster.

There was no such a thing as a cab in sight, so I approached the station master to inquire my way.

"Where lives Geheimrat—" I began, but there was no need to finish the sentence. Obviously there was but one Geheimrat at Grossbothen, for the station master cut in with:

"Geheimrat Ostwald? You go straight down the street there; and at the far end of the village, just at the top of the hill, you will come to his house."

I have heard of deserted villages, but I think I have never seen one that so fully deserved the title as did Grossbothen that December afternoon. As I trudged along the slushy street, no single mortal did I see; not even a child's face peering through a window. A late dinner or the post-prandial siesta seemed to have claimed every citizen of whatever age or station.

Finally, however, I came to what seemed to be an inn, and discovered a man in the court harnessing a team of horses.

Could I get a carriage and be driven to the home of Geheimrat Ostwald?

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That would be possible but it was scarcely necessary; for the house lies just down the street on the hill top yonder, indicating a place at least half a mile ahead.

It was not far, to be sure, but time was pressing and the walking very bad; so I preferred to ride. But I had to argue the case at some length before I could convince the inn keeper of the desirability of earning two marks by hitching up a horse. When his scruples had been overcome, however, he proceeded with alacrity, aided by his official household, consisting of a bucolic youth and a quaintly attired damsel who proceeded to dust and furbish the carriage that was drawn out of a shed where it seemingly had been housed for the season. A strange gentleman going to visit the Geheimrat must have the best that the establishment afforded.

Professor Ostwald's estate, at which we arrived presently, lies, as already mentioned, at the outskirts of the village, on a hilltop. There are attractive clusters of trees about the house, and a forest of pine and birch stretches away on the farther side. Professor Ostwald is a nature lover, and permits no shooting on his estate. So from his library window I saw a pair of deer browsing with the familiarity of tame creatures, and when we walked in the woodland we flushed a wild pheasant within a stone's throw of the house.

"LANDHAUS ENERGIE" AND ITS OWNER

The house itself is a commodious structure built by Professor Ostwald when he retired from Leipzig University about the year 1906. Entering one finds oneself in an atmosphere of books and

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pictures. There is also a well-equipped chemical laboratory, at one end of which stand an easel,—for Professor Ostwald is an amateur painter of no mean attainments. There is a conservatory, filled with plants in flower, without which no German household would be complete. The house is so planned that every corner of it is flooded with light, and all in all it is one of the most comfortable and homelike of dwellings. As it was designed by Professor Ostwald himself, it furnishes substantial evidence of the practical quality of the great chemist's mind.

As I had approached the house my eye had noted the placarded name "Energie," and I presently questioned Professor Ostwald as to the significance of this rather odd title.

"I gave my house this name," said he, "as a tangible expression of my conviction that energy is a reality. Energy is in point of fact as undeniable a reality as matter itself. Indeed, I define the unit structure of matter, the atom, as a focus of energy. You know perhaps that I have sometimes been disposed to doubt the existence of the atom as a material entity. The work of Sir Joseph Thomson and his followers has forced me to admit that the atom does exist. But it is a no more definite reality than is the energy with which all its activities are associated."

I was unable to induce Professor Ostwald to give a clearer expression of his conception of the structure of the atom. He seemed to regard this as still in the realm of the unknown, if not of the unknowable. That there exist focalizations of energy which have individual being and which may be termed atoms, he admits, in common with

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other chemists; but he appears to hold that any attempt to visualize the material conditions—if you please the architecture—of atoms, outruns our present knowledge, and hence would be essentially unscientific.

“About all that we can clearly admit,” he said, “is that the atom contains or is associated with electrical units—the electrons or corpuscles of Sir Joseph Thomson—which have about one thousand times less mass than the hydrogen atom. But some recent experiments seem to suggest that the electrons differ among themselves; hence it is probable that even this minute particle is not the ultimate structure of matter. What lies beyond the electron, however, toward the limits of the infinitesimal, it remains for the science of the future to determine.”

OSTWALD'S MOST IMPORTANT DISCOVERY

Our discussion of the atom led naturally enough, to a review of chemical progress in general, and I asked Professor Ostwald to tell me in a phrase what he considered his own most important contribution to the progress of the science with so many departments of which his name has been intimately associated for a generation. He answered without a moment's hesitation:

“I wedded the theories of Van't Hoff and Arrhenius. That constitutes my real contribution to the progress of chemistry. It was of course a much less original, and hence a much less important work than the conception of the theories themselves; yet it was not without its useful bearings on many departments of chemical research.”

That seemed to me a very modest estimate on

the part of a man whose classical researches in the analysis of acids and in the study of chemical equilibrium have caused his name to be quoted more frequently among technical writers on recent chemical progress than that of almost any other contemporary. Yet as this is the estimate of the worker himself, I am bound to accept it as authoritative, and in summarizing his work, it will be necessary to review the two theories which, to use his own words, he "wedded." It is quite worth while to make this review because the theories in question, thus combined and made fruitful, may be said to permeate the entire substance of modern chemistry. It is not too much to say that they constitute the essential structure of the newest chemistry.

The two theories in question are Van't Hoff's law of osmotic pressure and Arrhenius' law of electrolytic dissociation. To the average reader these doubtless are rather cryptic terms. Yet they really involve matters of no small degree of popular interest. Let me endeavor to interpret them concisely in popular language.

THE PHENOMENA OF OSMOTIC PRESSURE

Professor J. H. Van't Hoff, whose name is given to the important law of osmotic pressure, was by birth a Hollander, and his most important work was done while he held a professorship in the University of Amsterdam. More recently he was called to the chair of chemistry at Berlin University, but the earlier association must be borne in mind because he has himself recorded that he undertook the investigation of the laws of osmotic pressure at the instance of his colleague at the

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University of Amsterdam, Professor Hugo De Vries. Quite conceivably he might never have taken up the subject but for this association; so we have here another interesting illustration of the value of close association between men of genius who work in different lines of science.

The law of osmotic pressure has been said by Arrhenius to be "the most general law of matter that we know." The phenomena of osmotic pressure have application not merely in a great variety of laboratory experiments, but apply universally to the phenomena of plant and animal life. Yet the term has not become familiar in every-day speech, and when Van't Hoff made an address on the subject, on the occasion of his receiving the Nobel prize, he very wisely began by asking the question, What is osmotic pressure?

He answered the question in these words:

"If a solution—for example, of sugar and water—is separated from a pure solvent (in this case water) by a membrane which allows the water but not the sugar to pass through it then the water will be as it were sucked through the membrane to the solution. This results because there is a greater pressure on the side of the membrane to which the water comes; in other words, on the side of the solution. This pressure is osmotic pressure."

It should be explained that this phenomena of the passage of water through a membrane from one solution to another had long been familiar to students of plant and animal life. But like a good many other familiar phenomena it was a fact of obscure character, the cause of which remained quite unexplained.

The process of osmosis as related to the plant cell may be observed under the microscope. If the plant cell is bathed in a weak solution, as, for example, a dilute solution of common salt, the cell will absorb water from this solution and hence expand in size. If now the salt solution be strengthened gradually, there comes a time when the osmosis of water from solution to cell ceases; and the cell content and surrounding solution are said to be "isotonic." If still more salt is added to the solution, the process of osmosis begins to be reversed, the water passing out from the cell to the solution; the cell itself or its protoplasmic content correspondingly shrinking.

Details as to this phenomenon were particularly studied by Hugo De Vries, who called attention to the curious fact that solutions of different salts, when made of such strength that they are "isotonic"—that is to say, in equilibrium as regards osmotic pressure—with the same cell possess the same freezing point and vapor pressure. He could not explain this fact, however; and, indeed, the entire question as to why the water passed to or from the cell remained a mystery. The facts, however, were recognized as of the utmost importance, inasmuch as they involved the entire question of extraction of water from the earth by the roots of a plant, and the rise of sap in the tree, upon which the chief phenomena of vegetable life depend.

Somewhat similar studies of the animal physiologists led to corresponding results. The investigation of Donders and Hamburger, two Scandinavian physiologists, had particular interest. They showed that the red blood corpuscles are

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affected by the condition of the blood serum by which they are surrounded in a manner strictly analogous to the plant cell. If the solution surrounding the blood corpuscles is very weak, they give up their coloring matter, called hemoglobin, to the solution. In very strong solutions, on the other hand, the red blood corpuscles shrink, and finally sink to the bottom. Tests of the freezing points of solutions of different salts that had the same effect upon the blood corpuscles were found to conform to the results of De Vries.

VAN'T HOFF SOLVES THE RIDDLE

Anxious to solve the mystery of osmosis, which most physiologists had accepted as a fact without challenging its rationale, De Vries turned to his colleague, Van't Hoff, who was already famous through his studies of the space relations of the atoms,—otherwise stated, the architecture of the molecule. Van't Hoff, reviewing the evidence, was led to compare the facts of osmotic pressure with the facts of gas pressure. The familiar law of Boyle asserts that the pressure of a gas is proportional to the concentration of the gas. The same thing had been found by Pfeffer to apply to osmotic pressure so long as the membrane is impermeable to the dissolved substance. Similarly the pressure of both a gas and an osmotic fluid increases at a regular rate with increased temperature.

Given the clue by these facts, Van't Hoff studied the precise relations between the rate of osmosis and the amount of salt dissolved in an osmotic fluid. He had the idea that osmosis might be due to the pressure of the molecules of the dis-

solved salt against the obstructing membrane, precisely as the pressure of a gas is due to the action of its molecules. Mathematical calculations based on this assumption were so closely in harmony with the observed variations of pressure of different solutions, as to justify the belief that the assumption was valid. Hence Van't Hoff enunciated his important law of osmotic pressure, which has been stated as follows:

"The osmotic pressure of a dilute solution, containing a definite quantity of dissolved matter, is just as great as the gas pressure of this quantity of matter would be were it distributed in the gaseous condition over the same volume at the same temperature."

In other words, the particles of a substance in solution are moving about and attempting to escape in all directions precisely as are the molecules of a gas, and they push against the walls of the receptacle holding the solution precisely as a gas pushes against its encompassing ones. So significant is this pressure that Van't Hoff found it equivalent, in the case of a one per cent. solution of sugar, to two-thirds the pressure of the atmosphere. That is to say, if one ounce of sugar is dissolved in a hundred ounces of water, its molecules push in all directions with a pressure that aggregates about ten pounds to the square inch.

When osmotic pressure had thus been explained, the phenomenon of the absorption of water by the plant or animal cell, as already referred to, could be clearly understood. A cell bathed in a weak solution absorbs water not through any principle that could properly be called suction, but because the molecules of the cell

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content are pressing outward upon the cell membrane with such force that their push exceeds the counteracting push of the molecules in the outlying solution. Hence the cell is made to expand, and water from without simply percolates through the pores of the membrane to fill the space within. Contrariwise water is squeezed out of the cell when the outlying solution is stronger and hence exerts a more powerful pressure than the contents of the cell.

ANOMALIES EXPLAINED BY THE THEORY OF ARRHENIUS

It must not be supposed that Van't Hoff's explanation of the nature of osmosis met with immediate acceptance, or was free from the usual number of experimental tests that seemed to challenge its validity. On the contrary, so numerous were the objections found to the theory, that it probably would not have gained immediate vogue had it not chanced to find support in another theory that was propounded almost simultaneously. This was Arrhenius' famous theory of electrolytic dissociation, or ionization. Reference has already been made to this theory in another connection, but we must examine it here somewhat in detail because, as already intimated, it supplements the theory of osmotic pressure, and, in connection with that theory, forms the very substructure of the newest chemistry.

The essence of the theory of Arrhenius is the supposition that a large number of substances when dissolved in a proper medium—in particular, water—have some of their molecules split up into yet smaller particles called ions, half of

which are charged with positive, and the other half with negative electricity. Only such solutions as contain these electrified ions will conduct electricity; inasmuch as the passage of electricity through the solution is effected through the actual migration of the ions. A practical illustration of this is afforded by the familiar process of electro-plating, in which particles of metal, as copper or silver, are separated out of a solution and deposited at one pole of a battery.

The theory further assumes that all chemical reactions are due to the interrelations of the electrified ions; in other words, that all chemical action is in the last analysis electrical action. Evidence as to this is found in the fact that certain acids when in a highly concentrated state do not act on metals, or act very slightly, and at the same time are very poor conductors of electricity. Thus concentrated sulphuric acid may be kept in a metal receptacle and is a poor conductor of electricity. But if a portion of the same acid is diluted with water, it becomes exceedingly active, dissolving almost any metal with which it comes in contact; and at the same time it acquires the property of conducting electricity readily.

Now the relation between this theory of ionization as propounded by Arrhenius, and Van't Hoff's theory of osmotic pressure may not at first glance be obvious. Indeed the relation was not at first observed even by the propounders of the theories themselves. But as ultimately understood, the relation comes about in this wise: Van't Hoff's theory assumes, as we have just seen, that the osmotic pressure of any given

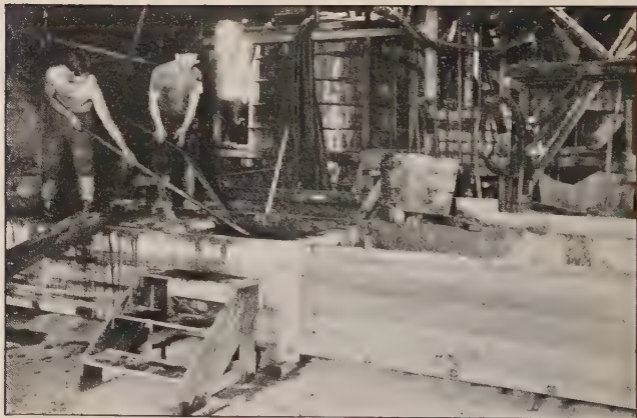
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solution is due to the aggregate push of the ultimate particles or molecules of the substance in solution. A solution, at given temperature, containing two million molecules will exert twice the pressure of one containing one million molecules. Unfortunately for the immediate acceptance of Van't Hoff's theory, however, there were found to be numerous instances in which the observed pressure of a given solution greatly exceeded the theoretical pressure as computed from the number of its molecules. Take for instance a solution of hydrochloric acid, each molecule of which consists of one atom of hydrogen united with one atom of chlorine. When a measured quantity of this acid is dissolved in a certain bulk of water, the observed osmotic pressure resulting is almost twice as great as would be expected from the computed number of its molecules. Such an observation would seem by itself to condemn the theory of osmosis as expounded by Van't Hoff.

But now comes the theory of Arrhenius to suggest that the molecules of hydrochloric acid in this aqueous solution, are almost completely dissociated into their electrified ions. That is to say, each molecule divides into a positively charged atom of hydrogen and a negatively charged atom of chlorine. This obviously results in the doubling of the number of particles. Each of these ions becomes in effect a molecule,—“molecule” being defined merely as the smallest particle of matter of any given substance that maintains isolated existence. And since the osmotic pressure depends upon the number of molecules and not upon their size, the abnormal



ENTRANCE TO A RADIUM MINE (BELOW), AND PILE OF
RADIUM ORE (CARNOTITE)



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PRELIMINARY ROUGH TREATMENT OF CARNOTITE (ABOVE),
AND EARLY CRYSTALLIZATION OPERATION

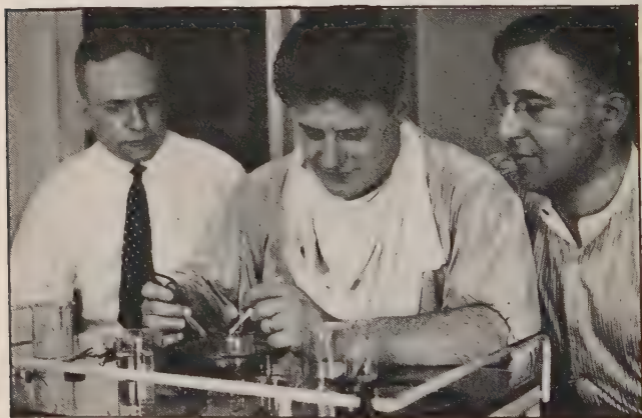


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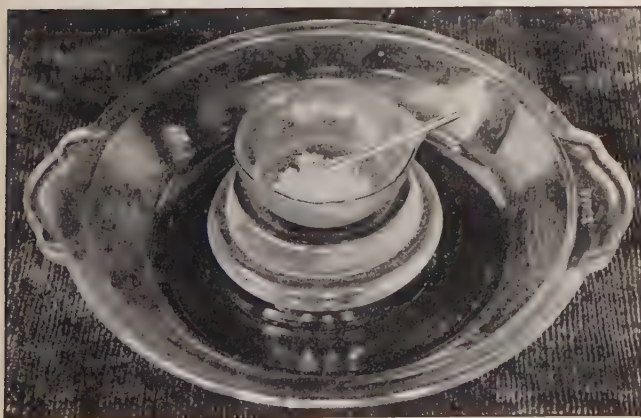
CRYSTALLIZATION ROOM IN FACTORY OF U. S. RADIIUM
CORPORATION (ABOVE), AND SECTION OF
CHEMICAL TESTING LABORATORY



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HIGH CRYSTALLIZATION RADIUM UNIT (ABOVE), AND
FINAL TESTS OF CRYSTALS OF RADIUM BROMIDE



RADIUM BROMIDE CRYSTALS (BELOW), AND RADIUM
PHOTOGRAPH (RADIOGRAPH) OF COINS AND KEY

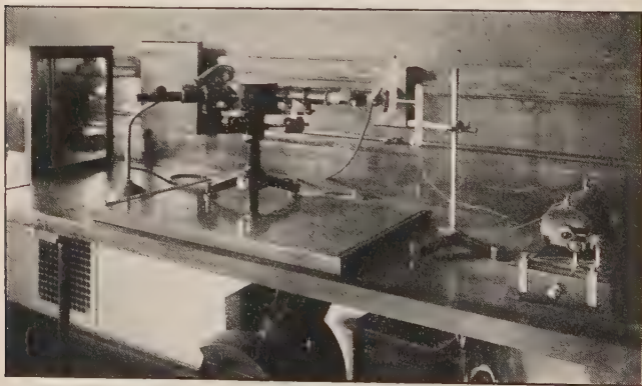
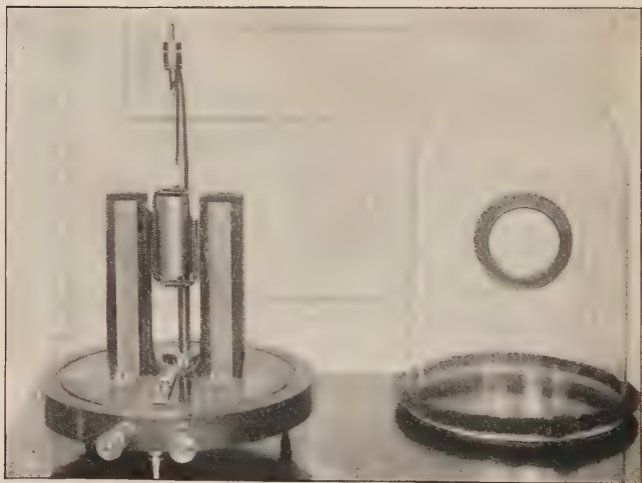


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ELECTROSCOPIC TEST OF RADIOACTIVITY IN THE LABORATORY OF
THE U. S. RADIIUM CORPORATION



MAKING WATCH-DIALS, NUMERALS, LETTERS, ORNAMENTS ETC., LUMINOUS BY
PAINTING WITH A RADIUM COMPOUND.



MIRROR GALVANOMETER FOR TESTING DELICATE
ELECTRICAL CURRENTS (ABOVE),
AND SPECTROSCOPE

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osmotic pressure of the solution of hydrochloric acid is seen to be in perfect conformity with the law of Van't Hoff which until thus interpreted with the aid of the theory of ions, it had seemed flatly to contradict.

Here, then, is a beautiful illustration of the way in which one scientific theory may come to the aid of another, clearly explaining away contradictions, and using established facts to prove a theory which, as otherwise interpreted, they seem utterly to disprove. But to get a clear view of the entire situation, it must be understood that the theory of Arrhenius was itself obliged to run the gauntlet of criticism before it could stand alone, much less come to the aid of any other theory. And it was here that Professor Ostwald was able to lend yeoman service from the very outset.

OSTWALD CHAMPIONS THE THEORY OF ARRHENIUS

It chanced that just at the time when Van't Hoff and Arrhenius were making their independent studies of osmotic pressure and ionization respectively, Ostwald was conducting a very extraordinary series of experiments to test the relative activities of some thirty-four different kinds of acids. These acids were tested with regard to their capacity to effect the so-called inversion of cane sugar, this chancing to be a chemical action of a type convenient for measurement, and an immense mass of data had been gathered enabling Ostwald to establish the gradations of chemical activities among his acids with the greatest nicety. Many of the observed facts, however, suggested questions as to the real nature

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of acids on the one hand and bases on the other, and of the union of these to form "salts," which the chemical theories of the time could not explain.

Thanks to these studies, and to the puzzling questions that had come to his inquiring and imaginative mind in connection with them, Ostwald was led to peruse with peculiar interest a brochure that came to him one day from an unknown student at the University of Upsala,—this brochure being in point of fact none other than Arrhenius' first exposition of his theory of ionization.

"I well remember the exact day when this document came to me," said Professor Ostwald, "because on the same day my wife presented me with a charming daughter, and the day is made memorable in a quite different way by the fact that I chanced to suffer at the moment the agonies of an ulcerated tooth. Under stress of varied emotions I sought to divert my mind by reading Arrhenius' brochure. My first thought was that this must be the work of some half-crazy enthusiast; but before the night was over I had come to the conclusion that I had before me what would probably prove to be a most important contribution to chemical theory. I saw at once how the data supplied by my experiments with the acids would enable me to test the theory of ionization and I resolved to put such tests into immediate effect in my laboratory."

To make a long story short, Professor Ostwald's experiments all tended to substantiate the validity of the young Swede's daring generalization. Ostwald found, for example, that when his

acids were tested as to their electrical conductivity, they marshaled into a series exactly corresponding to the series already established through study of their chemical activities. That is to say, an acid having very pronounced activity—let us say one rapidly converting cane sugar or quickly dissolving a bit of metal—would be found to be a conductor of electricity. Contrariwise a very weak acid would be but a poor conductor of electricity. And the relations thus observed corresponded so accurately as to reduce the matter to a very clear demonstration. So now Professor Ostwald had a new insight into the real nature of the processes that were taking place in his test tubes. He could understand, as never before, the real meaning of the words “base” and “acid” and “chemical affinity.” So-called “acid” properties he now knew to be due to the presence of free hydrogen ions charged with positive electricity; “basic” properties to the presence of ions composed of oxygen and hydrogen combined (called “hydroxyl”) negatively charged; “chemical affinity” or chemical action in general to the mutual attractions of ions respectively charged with negative and with positive electricity.

Finally the application of the theory of Arrhenius as thus substantiated by Ostwald, to Van't Hoff's theory of osmosis, was directly suggested by the observed fact that the only salts which exhibit abnormally high osmotic pressure are those which serve also as conductors of electricity when in solution. Moreover, a salt, which exhibits an excessive osmotic pressure, when in an aqueous solution, may cease to show abnormal behavior when another solvent is used; but in such case

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the new solution ceases to be a conductor of electricity.

In other words, a solution in which the molecules of a substance are not ionized exhibits precisely the osmotic pressure that would be calculated from its known number of molecules; and a solution in which the molecules are broken up into ions, as proved by the transmission of the electric current, exhibits the increased osmotic pressure which the increased number of its elementary particles would demand in accordance with Van't Hoff's law.

A SCIENTIFIC TRIUMVIRATE

Clearly to understand the progress of the new chemical theories, a few more words must be said about the mutual relations of the discoverers. The story has peculiar interest because it tells of harmonious personal relations entirely unmarred by those jealousies and rivalries that have so often been associated with the history of scientific discovery. Professor Ostwald had himself conceived at least anticipatory glimmerings of the facts of ionization before the work of Arrhenius was published. Had he been of different temperament he might have laid claim to a much larger share in the honor of discovery than he has ever sought for or been willing to accept. Some of his champions have attempted to prove from his own writings that he anticipated Arrhenius; but Professor Ostwald himself clearly and explicitly repudiates this idea, giving full and undivided credit to the great Swede.

How immediate and enthusiastic was Ostwald's acceptance of the new idea, was shown by the

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fact that he made a trip to Upsala soon after receiving the brochure of Arrhenius, to make the personal acquaintance of the young chemist. Finding that Arrhenius was but little appreciated at Upsala, where the members of the chemical faculty looked with more than suspicion upon what they regarded as the bizarre ideas of their pupil, Ostwald brought Arrhenius with him to Riga and gave him a position as assistant in his own laboratory. There the two men worked independently but in close association, testing and developing the new idea. The foundations were thus laid for a life-long partnership between the men who were henceforth to be known as the foremost chemists of their generation of their respective nationalities.

Van't Hoff, the foremost chemist of Holland, was presently brought into the coalition when Arrhenius went to Amsterdam to work in his laboratory. It was here that the final association between the theories of osmotic pressure and of ionization were worked out. Subsequently Van't Hoff became associated with Ostwald in founding the *Journal of Physical Chemistry*, a periodical which has doubtless had greater influence than any other in spreading broadcast throughout the scientific world a knowledge of the progress of the newest chemical ideas and theories.

In the work of making known the new theories through oral and written exposition, the influence of Ostwald was doubtless greater than that of either of his confrères. His lecture room and laboratory at Leipzig (to which he had been called from Riga) were soon famous as the foremost centers of chemical teaching; and the books that

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came from his pen combined scientific accuracy with clearness of exposition in a degree so unusual as to lead to their translation into many languages, and their wide dissemination in all countries where science has a foothold.

But his work as teacher and expositor did not prevent Professor Ostwald from continuing his experimental work, as a long line of technical publications amply testifies. His classical work on the acids and his share in establishing the theories of Van't Hoff and Arrhenius constitute, however, as already pointed out, his great contribution to the progress of contemporary chemistry. It happened here, as so often elsewhere in the history of science, that the new generalizations require to be tested, applied, and interpreted for a decade or two before the field is prepared for the advent of another great generalization. Lyell, the famous geologist, pointed out long ago that every new theory in science must pass through three stages. First people say that it is not true; then that it is not important; finally that it is not new. The theories of osmotic pressure and of ionization have not failed to conform to this rule. That the chemical world has so quickly changed from skepticism to enthusiastic acceptance of both the truth and the value of the new ideas, and has so early given full recognition to the discoverers, must in no small measure be ascribed to the extraordinary influence of Professor Ostwald.

CHAPTER V

SIR J. J. THOMSON AND THE WONDER- WORKING ELECTRON

WERE one less familiar with the personality of great men of science, one might expect to find so famous a personage as Sir J. J. Thomson ensconced in an elaborate series of sumptuously furnished laboratories and offices, with the surroundings of luxury, even of magnificence. Such a setting would surely be appropriate for the discoverer of that idol of the modern scientific world, the electron.

At the very least one might expect that the Professor of Experimental Physics at Cambridge, who chances also to be the world's foremost living physicist, would be hedged about by a certain amount of formality,—a uniformed lackey or two at the doorway; some guards, assistant professors, or laboratory assistants to pass before one could reach the sanctum of the master.

But the reality is as different from all this as could well be imagined.

As you enter the dingy hallway of the Cavendish Laboratory, there is not so much as an office boy to be seen. You are fortunate if you can discover a chance student of whom to inquire your way. You pass up the inornate stairway, made notable only by the portraits of celebrated physicists that flank the wall, and are ushered without the slightest semblance of ceremony into a bare little room where a man with a wonderful fore-

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head overtopping an ascetic face and a lean, frail-seeming body, sits at a high flat-topped desk, obviously absorbed in thought. A fine painting of Sir J. J. Thomson has caught your eye as you ascended the stairway, and you instantly realize now that you are in the presence of the great physicist himself.

THE PERSONALITY OF THE CAVENDISH PROFESSOR

But for a few moments the absorbed thinker scarcely notices your presence. He rises, to be sure, and extends his hand with every evidence of courtesy. He even seems to give attention to your words. But his eyes look beyond you, and it is evident that his mental vision is focussed on some abstruse mathematical or physical problem, which he must carry to a convenient stopping-place, or store in some accessible mental pigeon-hole, before he can give attention to any other topic.

Meantime you are enabled, without seeming impertinence, to take in every detail of the figure before you,—the figure of a typical scholar, attired in a light gray suit, with necktie askew, and the general aspect of one who gives scant thought to his personal appearance. A second glance shows you that the seemingly frail body is wiry and instinct with energy. It is the body of a tireless worker who has lost just one week's time from the laboratory through illness in a quarter of a century; who goes up stairs two or three steps at a time; and who seems not to know the meaning of fatigue.

The problem-solver has reseated himself mechanically on a high stool, one elbow resting upon

the desk, over the surface of which books and papers are scattered in seeming confusion. Aside from two or three exceedingly plain chairs, the only remaining furniture is a small table with table cloth, obviously used in serving tea, and a plain bookcase with a few books in one corner. On the wall there is a large painting of Clerk-Maxwell and his wife; and there are small portraits of Faraday, Huyghens, Rowland, Helmholtz, and Van't Hoff,—two Englishmen, an American, a German, and a Hollander. Clerk-Maxwell was the first Cavendish Professor. His chief work was done here, and there are souvenirs of his activities everywhere about the Cavendish Laboratory.

Very soon Professor Thomson has shelved his mental problem, and he turns with full seeming interest to his visitor, and gives him the same concentrated attention that he bestowed upon his musings. The impression that one gains at once and retains is of a man utterly simple in manner, without the slightest trace of affectation. He talks about his work without reserve, but always with moderation and without the slightest hint of dogmatism. His voice is deep, full, and resonant. His words have all the precision that one would expect. He has a peculiarly charming, deprecating smile, as he refers to his own work. A certain sternness of aspect in repose; yet at all times the kindest of faces.

One gains the impression that here is a man truly great in spirit and character as well as in intellect; if not the greatest living man of science, surely one of the greatest. His kindness of manner, modesty, affability, and lack of dogmatism

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and egotism, remind one forcibly of the late Lord Kelvin.

THE SMALLEST AND MOST IMPORTANT THING IN THE WORLD

My conversation with Professor Thomson naturally focussed upon his newest discoveries. He talked freely about the work that he had in hand at the moment, and showed me his newest apparatus and some extraordinary photographs of atoms, of which I shall have more to say presently. But in order to make things clearly intelligible, we must first go back and review briefly the earlier work of the great physicist, which led to the discovery of what is, so far as we know at present, at once the smallest and the most important thing in the world, namely, the unit structure of matter which we term the electrical corpuscle, or electron.

Incidentally, we may note that the word electron is now used almost universally, altho Professor Thomson originally christened the electric unit with the name "corpuscle." I suggested to the discoverer that the rechristening had been a sort of impertinence on the part of the scientific world; but it is another evidence of his breadth of mind that he only smiled and seemed amused at this view.

But whether called corpuscle or electron, the infinitesimal in question is without doubt the most interesting thing that has been revealed to the world of science in our generation. In the words of Poincaré the electron has conquered modern physics. This famous French physicist declared that Professor Thomson's hypothesis enables us to

group together all known facts concerning electric discharges and radioactive substances; that it leads to a satisfactory theory of optics and electricity; that it seems likely to embrace shortly the principle of thermo-dynamics through the intermediary of radiating heat; that it enters the domain of mechanics, and furnishes a simple presentation of the essential properties of matter, enabling us to penetrate farther into nature's secrets than our predecessors were ever able to do.

In a word, the discovery of the electron has had an almost revolutionary effect upon the attitude of the scientific world toward the most fundamental problems of matter and of energy. Moreover it has thrown light on a multitude of things that have popular every-day interest. Were it not for this remarkable little body there would probably be no heat in the sun; no electricity and no light anywhere; no life, vegetable or animal, on the earth; it is even probable that there would be no sun, no earth, no material thing of any kind in existence.

Banish the electron, says the science of to-day, and you annihilate the universe.

Yet the very existence of this all-essential corpuscle was utterly unsuspected until Professor Thomson ferreted it out and revealed its universal presence. It is surely worth while to learn how this feat was accomplished, even at the expense of a half-hour of close attention. Unless the reader is willing to give such attention, I fear I can not hope to make him see his way clearly into the newly discovered realm of the infinitely minute where the electron holds undisputed sway. But, granted a little close thinking, and the mastery of

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a few terms that are unfamiliar simply because they are new, the story of this greatest discovery of our generation may be understood, as regards at least its general outlines, by the most untechnical reader.

STEPS TOWARD A GREAT DISCOVERY

The discovery came about as the culmination of a long series of experiments, extended over a period of seventeen years, and having to do with various aspects of the question as to what happens when a charge of electricity is made to pass through a gas. To understand the essentials of the problem, it must be known that a portion of perfectly dry gas, at ordinary temperature, and under ordinary conditions, is almost absolutely impervious to an electrical current of ordinary strength. Under changed conditions, however—as, for example, through being intensely heated—a gas may conduct electricity readily. Professor Thomson has recorded that immediately after his election to the Cavendish professorship in 1884, he instituted investigations aimed at the solution of the numerous interesting problems that arose in connection with this matter of the electrical conductivity of gases; “and since then,” he adds, “I think there has never been a time at which I have not had some experiment in hand on this subject.”

He was led to the investigations, he says, by his belief that whenever a gas conducts electricity some of its molecules must have been split up, and that it is the molecules that have been thus modified which imparted electrical conductivity. This idea (borrowed from the new chemistry of Arrhe-

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nus) was correct, but the nature of the splitting up of the molecules was not revealed until countless experiments had been made. Ignoring for the moment the question as to just what has happened to the gaseous particles to render them conductors of electricity, let us recall that a gas possessing this property is said to be "ionized." Its conducting particles are termed "ions."

The old method of ionizing a gas was to pass the gas over an incandescent plate or through a flame, or to subject it to an extremely powerful disruptive charge of electricity,—an artificial streak of lightning. These methods obviously complicated the experiments, and progress was difficult until Professor Roentgen's famous discovery of the X-ray placed a new instrument in the hands of the physical investigator. All over the world physicists began testing the properties of the mysterious new manifestation of energy. The first thought of Professor Thomson at the Cavendish Laboratory was to discover whether the X-ray would in any way affect his particular problem as to the electric conductivity of gases. A test as to this was readily made, and it was found that the Roentgen ray would discharge an electroscope. That is to say, it would ionize the air about the electroscope, rendering it capable of conducting electricity.

AID FROM THE X-RAY

It was found that a gas which had thus been ionized by exposure to the X-rays retained its capacity to conduct electricity long enough to allow its properties to be examined. "It was further found," says Professor Thomson, "that the

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conductivity could be filtered out of the gas by sending it through a plug of glass wool or allowing it to bubble through water; thus the conductivity was due to something mixed with the gas. That this something consisted of particles charged with electricity was shown by the fact that the conductivity could also be removed from the gas by applying electric force to it. This force would, of course, attract or repel electrified particles and thus withdraw them from the gas; it would not, however, affect particles that were not electrified.

"Thus the conclusion was arrived at that when the Roentgen rays pass through a gas they produce a supply of positive and negative particles ["ions"], which by moving through the gas under electric forces endow it with conductivity. If the gas is left to itself, the positive and negative particles reunite, and then the gas gradually loses its conductivity."

A number of workers at the Cavendish Laboratory, including the afterwards famous Professors Rutherford, Townsend, McClelland, Langevin and C. T. R. Wilson, assisted in a variety of researches, through which the characteristics of the electrified particles or ions in the ionized gas were subjected to all manner of tests. The velocity at which the particles move through the gas when attracted by electric forces was measured, as well as the rates at which they diffuse through different gases, and the laws were discovered according to which the positive and negative particles reunite; until presently, as Professor Thomson declares, "the properties of these gaseous ions were known with much greater precision than those of the electrolytic ions in liquids, which had been

studied for a very much longer time." So rapid may be the progress when master workers combine forces, under supremely competent leadership.

Yet there was at first no evidence to show that these gaseous ions were different in size or general character from the ions found in liquids, with which the researches of Arrhenius and Ostwald had recently made the scientific world familiar. The clue to their real character was gained indirectly through Professor Thomson's study of the phenomena that result when electricity is discharged through a Crookes tube,—that is, a bulb or tube from which the gas has been almost entirely removed.

CATHODE RAYS PERMIT A SEMI-FINAL EXPERIMENT

Nearly everyone nowadays has seen a so-called Crookes tube, and witnessed the curiously vivid light effects that result when electricity is sent through it, producing a stream of so-called cathode rays. It is these cathode rays which, when they impinge on the wall of the tube, set up the vibrations that we call Roentgen or X-rays. The cathode rays themselves were discovered by the German, Hittorf, and had been studied for some time before they were called to the attention of the general public by Roentgen's discovery.

Meantime two entirely different views as to the real nature of the cathode rays were held by physicists. The Germans inclined to the belief that they are electric waves in the ether, allied to those which Hertz had recently demonstrated, and which were presently to be utilized in wireless telegraphy. English physicists, on the other hand, were most inclined to the view that the cathode

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rays consist of electrified material particles thrown off from the positive pole or cathode. It was in making tests to decide between these views that Professor Thomson was brought one stage nearer to his great discovery.

The tests were made by passing a stream of cathode rays through a magnetic field, to observe whether the rays were deflected from the line of direct flight by the influence of the magnet. Similar tests had previously been made, with negative results, by Hertz; but Professor Thomson's experiments proved beyond question that the cathode rays are deflected by a magnet.

This definitely proved that the cathode ray is composed of particles, inasmuch as mere ethereal vibrations would not be influenced in this way by the magnet.

Not only this, but the experimenter was able to measure the exact angle of deflection, and he was soon made aware that the rays were turned aside by magnetic influence of known power to a far greater extent than they would be, according to calculation, if the particles had a mass approaching even that of a hydrogen atom, the smallest thing then known. Indeed, the experiment seemed to make it clear that the cathode particles must be at least a thousand times smaller than the hydrogen atom.

This seemed incredible, for chemists had long supposed the hydrogen atom to be the smallest particle of matter in existence. Yet the only alternative was to suppose that the cathode particles carried each a charge of electricity a thousand times as great as the unit charge carried by

an atom of hydrogen in an ionized liquid; and this seemed equally incredible.

To decide the dilemma, further experiments were necessary. Obviously a crucial test would be made if the actual charge of electricity carried by a cathode particle could be measured.

SEEING THE INVISIBLE

But how determine this charge? The difficulties of making such a test would seem to the ordinary mind utterly insurmountable. But fertility of invention is one of Professor Thomson's most characteristic traits of mind. His laboratory assistant, commenting on this in a talk I once had with him, said: "If an experiment fails, Professor Thomson will invent a dozen other experiments at once to complete the test."

So in this particular case it was not long before the imaginative physicist found a way of testing the electric charge of the new particles. At least he tested the charge of the negative particles in ionized air, which comes to the same thing, for the experimenter had correctly surmised that these particles and the cathode ray particles are identical. As we now know, both are, in point of fact, electrons.

A good deal of abstruse mathematical calculation, and sundry experiments that are too technical for popular exposition entered into his tests; but fortunately the most conclusive and demonstrative experiments were of a type at once picturesque and readily comprehensible. They resulted, extraordinary as this must seem, not only in demonstrating the infinitesimal size of the particles, but in making the particles visible, by

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causing droplets of water vapor to condense upon them.

It is familiar knowledge that when air containing watery vapor is cooled, the vapor tends to condense on particles of dust or any other minute objects that may be floating in the air. When air is entirely freed of impurities, it may be cooled to a much greater degree without causing vapor to condense, there being no nuclei about which the tiny droplets may collect. But experiments made at the Cavendish Laboratory just at this time by C. T. R. Wilson showed that if a perfectly pure portion of air in an appropriate receptacle is ionized by the passage of Roentgen rays, and then cooled by expansion, the electrical ions will serve as nuclei of condensation, and a cloud of water vapor will be formed. Professor Thomson saw at once that this fact might supply a means of counting the ions and so determining their individual electrical charges.

His line of reasoning was this: When an ionized gas is allowed to expand suddenly to a measured extent, the amount of cooling that will result from such expansion can be accurately calculated, and hence the total amount of vapor that will be deposited on the appropriate nuclei can be estimated. The individual particles are of course far too small to be measured directly, but fortunately their size may be estimated through observation of the rate at which they sink through the air. Sir George Stokes had developed a formula from which the size of the particles making up a cloud of vapor may be accurately calculated, if the length of time required by the

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upper surface of the vapor cloud to settle through a measured distance is noted.

By utilizing this method Professor Thomson calculated the size of the individual droplets of water condensed about the electrical ions. The size of the individual droplets being thus known, and the total amount of condensed vapor being already known, it is obviously a mere matter of division to determine the number of droplets in a given air space—each droplet representing of course an electrical ion.

THE ELECTRON REVEALED

It remained now only to measure the total electrical charge conveyed by the ions in a given space to determine by equally simple division the charge carried by each individual ion, this being, it will be recalled, the essential item of information required to determine whether the gaseous ions were much smaller than the hydrogen atom, or whether they merely carried an excessive charge of electricity.

The test showed, quite as Professor Thomson had anticipated, that each gaseous ion carried only the unit charge of electricity; that is to say, the same charge that a hydrogen atom in solution carries, as previously determined by well-known experiments. It followed then (recalling the experiment of deflecting the cathode ray above outlined) that the electrical particles in question are exceedingly minute; having, in point of fact, less than one-thousandth of the mass of the hydrogen atom.

And so at last the electron was revealed as an entity of inconceivable minuteness; a thousand

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(more accurately 1700) times smaller than the smallest thing of which science had hitherto had knowledge; a thousand *million* times smaller than the minutest particle that the most powerful microscope makes visible; yet a perfectly tangible and demonstrative entity, carrying always its unit charge of negative electricity. "Subsequent investigations," says Professor Thomson, "have shown that these negatively charged particles are widely diffused and form a part of every kind of matter, and play an important part in many physical phenomena,"—a very modest and conservative statement of the rôle of the electron, as we shall see.

THE UNIT CHARGE OF ELECTRICITY

It was presently discovered that these particles owe their mass to their speed of flight; that therefore they are not properly to be considered as matter at all, but only as units of electricity; and that as such they have precisely the same character regardless of the kind of gas in which they are produced. In other words, when a gas is ionized the liberated negative electrons are precisely the same whether the atoms from which they are liberated are those of nitrogen, hydrogen, oxygen, or some other gas.

The electron thus appears as a unique unit particle carrying a unit charge of electricity, and capable of associating with every form of matter.

The theory that this newly discovered infinitesimal particle, the corpuscle or electron, is really the unit structure of electricity, made instant appeal to the imagination of the scientific world. There were many facts at hand that seemed to give it

plausibility. It was known, for example, that atoms of different kinds of matter carry different charges of electricity when ionized in solution, and that these charges are always direct multiples of the unit charge carried by the hydrogen atom.

This fact had suggested to Faraday the idea that electricity in its ultimate nature might be made up of particles, just as matter is made up of atoms. The idea had been countenanced by Clerk-Maxwell, and Helmholtz had brought it again prominently to the attention of the scientific world. The discovery of the electron, however, gave a tangibility to the theory that it had hitherto lacked. Here, seemingly, was the unit structure of electricity actually revealed and demonstrated. Moreover this unit of electricity was found to be linked and associated with the atoms of matter in a way that suggested an explanation of many hitherto inscrutable phenomena.

ALL CHEMICAL ACTION DUE TO THE ELECTRON

There had, for instance, been no explanation hitherto forthcoming of the familiar chemical fact that some atoms of matter associate themselves in pairs whereas others associate in groups. Thus an atom of hydrogen can link itself with only a single atom, whereas an atom of oxygen has, as it were, two bonds, or so-called affinities or "valencies." A familiar illustration is furnished by the molecule of water which contains always two atoms of hydrogen linked with one atom of oxygen. Atoms having a single bond are said to be univalent; those having two bonds bivalent; those having three bonds trivalent, etc.

These are facts familiar to every chemist, but

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hitherto quite unexplained. But now the plausible suggestion was made that the "affinity" of an atom for other atoms might be an electrical phenomenon due to the loss or gain of one or more electrons. Under ordinary conditions an atom might be supposed to constitute an electrically neutral system or a system in equilibrium, owing to the attractive influence exercised over its electrons by the charge of positive electricity, which was supposed to be always associated with the atom. More will be said about this positive charge later, but for the moment let us accept it as present without attempting to explain its character. Let us only suppose that it precisely balances the aggregate negative charge of electricity given the atoms by its electrons, so that the atom under normal conditions would be electrically neutral.

But now suppose that through some disturbance in a system, a single electron were to escape,—this being precisely what happens when a gas is ionized. The atom from which the electron has escaped is no longer electrically neutral, but has its positive charge in excess, and therefore it tends to attract any free electron or negatively charged atom that comes into its neighborhood. Such an atom, lacking one electron, would exercise a single bond of attraction; or, in chemical phraseology, would be univalent. Similarly an atom from which two electrons had escaped would be bivalent; one from which three had escaped trivalent, etc.

Meantime some other atom to which a free electron had flown would have its electric neutrality disturbed in the opposite direction, its

negative electricity being now in excess; and this atom also would be univalent, bivalent, or trivalent, according as it received one, two, or three electrons in excess of its normal number.

Now this disturbance of the electrical equilibrium of atoms and groups of atoms is precisely what is observed when a salt is dissolved in water; the resulting condition being described, as we have previously seen, as electrolytic dissociation, or ionization. To take a specific instance, we have seen that a quantity of common salt, which is technically known as sodium chlorid, when in solution produces positively charged ions of sodium and negatively charged ions of chlorin. This fact, which Arrhenius demonstrated, and which is one of the basal facts of the new chemistry, could be explained only in general terms, until the theory of electrons was called into requisition. Then it was seen that the supposition that the sodium atom had lost an electron which had gone to the chlorin atom would plausibly account for the observed facts.

In this view, then, all chemical action whatever is due solely and exclusively to the migrations of electrons. Were the electrons to cease their activities, all matter would become static. It would become impossible to make a fire, for example, since combustion is a chemical process. But this would be of no consequence, for there would be no living thing on the earth, since the life processes are also chemical, and a creature whose cells lacked active electrons must instantly die.

Such is to-day the widely accepted view of chemical action.

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THE ELECTRON AS THE UNIT STRUCTURE OF ALL MATTER

But, if we are to accept the new theories at their face value, the influence of the electron is even more profound than all this suggests. For it may even be made to appear that the electron is not merely the originator of all chemical action, but the basal structure of matter itself; in other words, that, in the final analysis, there is nothing in the material universe but electrons.

Professor Thomson was early led to this utterly dumfounding idea by a consideration of the observed properties of the electron. The idea is doubly startling when we recall that the electron itself, as we have just seen, is not strictly speaking a material substance, but a center of electrical energy. The theory thus presents the curious paradox of regarding all matter as made up of aggregations of particles of electricity, which is not matter at all in the ordinary acceptance of the word.

As originally propounded, Professor Thomson's theory suggests that the entire mass of the material atom is made up of electrons which are circling about in a sort of planetary system. There will be about one thousand of these electrons in the system which we call a hydrogen atom. Heavier atoms must be supposed to be built up of multiples of the group of electrons constituting the hydrogen atom; so that in the case of very heavy atoms the number of electrons would be large. The atom of mercury, for example, would contain about 200,000 electrons.

Professor Thomson set about to make an elaborate mathematical calculation to determine

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whether he could construct a theoretical atom out of groups of electrons which would plausibly explain the facts of chemical valency, and in harmony with the facts of the well-known periodical system, according to which the same chemical properties tend to recur at regular intervals when the elements are arranged in the order of their atomic weights.

It was found that the electrons could be theoretically arranged in groups which are singularly in harmony with the observed facts of chemical valency. The groupings suggested by Professor Thomson are too complicated to be reproduced here; it suffices to record the fact that theory was made to harmonize so well with observation as to give the electron theory of the atom a large measure of probability.

But it is interesting to record that when I came to talk with Professor Thomson with regard to his newest views in the matter, I found that he had considerably modified his original theories. "Some experiments recently made here in the laboratory," he said, "tend to suggest rather strongly that the hydrogen atom, instead of being composed of a large number of electrons, in reality contains only a simple electron. The number of electrons in different atoms would then correspond to the atomic weights of those atoms as compared with hydrogen. That is to say, helium would contain four electrons; oxygen sixteen; mercury two hundred, etc. This simplifies the original view of the relation of the electron to the atom. It modifies the theory without overthrowing it." It implies that the atom is not composed solely of electrons.

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WHAT IS THE ELECTRON REALLY LIKE?

Putting aside the question as to whether the electron is the sole constituent of matter, however, there remain other elements of the accepted rôle of this wonderful corpuscle that give it transcendent interest. But before we speak of these, let us endeavor to gain a mental picture of the electron itself.

What shall we suppose this ultimate particle, in which matter and energy seem to blend into one, to be really like?

Professor Thomson answered this question, soon after the discovery was made, by suggesting that the electron is in effect an infinitesimal magnet, the point of union of lines of magnetic force which physicists speak of as "Faraday tubes." Most readers have probably seen the familiar experiment in which the lines of force that radiate in curves connecting the poles of a magnet are demonstrated with the aid of iron filings. It is familiarly known, too, that our earth itself is in effect a giant magnet, and that the direction of its lines of force, or Faraday tubes, may everywhere be tested with the aid of the compass needle.

Briefly, then, Professor Thomson conceived that the electron is simply a magnet—or if you prefer, a world—in miniature,—a mere point in space where magnetic lines of force converge. According to this view the electron would not have any definite physical bounds of size, since its infinitesimal Faraday tubes spider-web out into space to indefinite distances.

It is rather difficult to get a clear idea of the electron as thus visualized. The idea of lines of

magnetic force radiating into space and exerting magnetic influence to an indefinite distance would be perhaps utterly unintelligible to the average mind were it not that we have the ever-present magnetism of the earth, with its influence on the compass needle, to give us tangible demonstration; and had not most of us, as children, tested for ourselves the mysterious powers of an ordinary magnet.

In talking with Professor Thomson I found that he had not fundamentally altered his conception of the electron as a center of magnetic influence. He did, however, put forward the rather puzzling suggestion that the electron may be the end of a single Faraday tube or line of magnetic force, instead of the converging point of an infinite number of such tubes or lines. As we have no tangible analogy in a magnet of manageable size having only one line of magnetic influence, I found it more difficult to grasp this new idea of the electron than to cling to the older idea of which it is a modification.

I did not gather, however, from what Professor Thomson said, that he put forward the new suggestion as definitely supplanting the old, but only that he wished to emphasize his belief that a single line of magnetic influence in connection with an electron would account for the observed phenomena. It must be understood, of course, that the electron is conceived as always in a condition of violent agitation or rapid rotation, so that even were it provided with only a single Faraday tube, its magnetic influence would still be exerted in every direction.

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ACTIVITIES OF THE ELECTRON

The activities of the electron must, indeed, be borne constantly in mind by any one who would gain a clear idea of this extraordinary unit structure of matter and energy as the modern physicist conceives it. To speak of an electron at rest would be almost a contradiction of terms. Even when held in thralldom, as in the substance of an atom, the electron must be conceived as revolving with inconceivable speed in a planetary orbit.

Small as the atom is, it is large enough to provide relatively vast space in which the infinitesimal electrons may revolve, as the earth and its companion planets revolve about the sun. The speed of the electrons and their mutual repulsion would result in driving them instantly off into space, were it not that they are held in check by the attractive influence which we have hitherto vaguely referred to as the positive electric charge of the atom, but which we may ultimately be obliged to think of as a centrally located positive electron.

So powerful is this influence that ordinarily the revolving electrons are held in a stable planetary system. Equilibrium may be disturbed by various outside influences, such as the application of extreme heat or the impact of the Roentgen ray; in which case one or more electrons—outlying planets of the system, perhaps—break away from their moorings, so to speak, and go dashing off comet-like into space; the atom whose planetary system is thus shattered being now spoken of as an ion.

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THE ELECTRON AS GENERATOR OF ELECTRICITY, MAGNETISM, AND LIGHT

The liberated electron, under ordinary conditions, will quickly be drawn into a planetary system again, and the condition of equilibrium will be re-established. But under certain exceptional conditions a channel may be provided along which the electron may travel, together with a multitude of its fellows, and we shall then have developed what we term an electric current. When it is understood that the atoms of solid substances, no less than those of liquids and gases, contain detachable electrons, it will be seen that the entire phenomena of the passage of an electrical current, let us say along a wire, through a liquid, and through an ionized gas, may be explained in terms of the electron theory.

It should be explained that the electrons are proved to be capable of taking on enormous speed. In full flight their rate of progress approximates the speed of light—that is to say about 186,000 miles per second. Professor Thomson has calculated that an electron in dashing from one atom to another may change its line of flight and dart in and out of one atomic system after another to the number of forty million times per second. Such figures are, of course, quite incomprehensible, but they represent calculations based on delicate and accurate experimental observations.

Similarly we are told that the repulsive power which one electron manifests toward another is relatively enormous,—“a trillion trillion times greater than the attractive power of gravitation.” It is even suggested that if a single gram of pure negative electrons (one holds a gram of an ordi-

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nary substance on the point of a knife) were placed at the north pole, and another gram at the south pole, these two tiny masses of electricity "would repel each other with the force of 112,000,000 tons, and this in spite of the fact that the force decreases with the square of the distance." These mystifying estimates are cited here on the authority of Mr. E. E. Fournier d'Albe.

That all matter is not disrupted by the mutual repulsions of the electrons it contains, is held to be due to the fact that the repulsive influence is everywhere neutralized by the attractive influence of the positive electric charge. Moreover it is believed that for some entirely unknown reason electrons cease to repel each other when they are progressing in parallel lines at excessively high speed. Otherwise it would not be possible to conduct an electric current, consisting of streams of electrons, along a wire, as their mutual repulsions would scatter them into space.

When we have thus postulated the electron as at least an important element in the building up of matter itself, as the sole agent in chemical action, and as the unit structure of electricity, we have given it a commanding position; but we have by no means exhausted its rôle. For it is held that when the progress of the electron is suddenly accelerated or retarded its vibrations disturb the universal ether in such a way as to produce electromagnetic waves, of the type which the wireless telephone has brought prominently to public attention. And then, that the influence of these subtle particles may be brought still more closely home to all of us, we are told that the activities of the electron, as it rotates and revolves

in its tiny orbit, are the sole source of those waves in the ether which our eyes interpret as light.

Until the advent of the electron, the origin of light waves was an entire mystery. So long as the atom was regarded as a unit structure, we had no way of explaining the observed fact that the atoms of different kinds of matter split up the rays of light into different so-called spectra, each with characteristic but unintelligible lines. Rowland, the celebrated maker of diffraction gratings, had suggested that the simplest atom must be more complex in structure than a piano; but the nature of its mechanism was not even guessed at. But now that we have come to think of the different atoms as made up of different groupings of electrons, both the diversity and the complexity of their spectral lines may be at least provisionally explained.

THE MYSTERY OF GRAVITATION

The electron having come so near to explaining the entire sum of phenomena of the physical and chemical worlds, it is natural that its aid should have been invoked in the endeavor to solve that profoundest mystery of all, the nature of gravitation. The phenomena of gravity are brought incessantly to our attention, and Newton's great law brought the phenomena into one all-comprehending system. We know that every particle of matter in the universe attracts every other particle of matter with a force proportional to the product of the masses of the two bodies and inversely as the square of their mutual distance. But the nature of the force which thus unites the particles of matter has continued altogether unexplained.

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It would be going too far to assert that the electron theory has solved this perennial mystery. But, on the other hand, it must be recorded that an attempted explanation has been made which at least has certain elements of plausibility. It has been suggested that the observed attraction between electrically neutral bodies—that is to say, between ordinary masses of matter—is due to a “residual action of the opposite electrifications which they contain, so that the attraction between two charges of opposite sign is not equal to, but slightly greater than, the repulsion between two similar charges of the same sign.”

It is held by the workers at the Cavendish Laboratory that the recent discovery of the fundamental difference in the nature of positive and negative electricity lends plausibility to this suggestion. Professor Thomson, with Mr. Southern, has made pendulum experiments which seem to support the hypothesis that the weight of a body is affected to some slight extent by the state of its electrification.

Should these experiments be repeated and verified, it may chance that the perennial mystery of gravitation will be brought—along with electricity, magnetism, light, heat, and matter itself—within the all-comprehending scope of the electron theory.

CARRIERS OF POSITIVE ELECTRICITY

As we have followed the story of the electron, with its charge of negative electricity, we have given only incidental recognition to the fact that wherever there is in Nature a charge of negative electricity there is always a counter-balancing

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charge of positive electricity. The electron with its negative charge chanced to lend itself more readily to investigation, and it long monopolized the attention of the experimental physicists. But it was characteristic of the vitality of mind of the discoverer of the electron, and of his unflagging mental initiative, that he should have turned his attention in recent years to the converse side of the problem, seeking to fathom the secrets of positive electricity as he has already fathomed those of its negative counterpart.

It should be explained that the carrier of the positive charge of electricity had been more or less in evidence throughout the experiments on the ionization of gases. We have seen that one factor in the ionization of a gas consists in the liberation of electrons each bearing a unit charge of negative electricity. These electrons have been torn, as it were, from the structure of the atoms of gas. Each atom from which an electron is removed has its electrical neutrality disturbed, and because of the withdrawal of the negative charge carried by the electron, the remaining portion of the atom manifests the presence of a charge of positive electricity.

As the positive ion thus formed consists of an atom from which only the infinitesimal mass of the electron has been removed, it is obvious that the positive ion is enormously large in comparison with the size of the electron. Partly because of its size, the positive ion is less easily tested with the aid of the electrical and magnetic currents. It chanced that the positive ion does not so readily cause condensation of vapor as does the electron,—an observed difference not readily explicable.

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These facts partly account for the comparatively slow development of knowledge regarding the positive ion. The main reason, however, why the study of the electron went forward so much more rapidly was that the conspicuous character of the cathode rays in a Crookes tube—which rays, as we have seen, consist of streams of electrons—made them the subject of universal interest and experiment.

CANAL RAYS

But presently it occurred to thoughtful observers that, following the analogy of the flow of electric currents through liquids (in which, as is well known, positive ions migrate in one direction, while negative ions are going in the other), there should be some counter-stream of positively charged ions in the Crookes tube, to offset the observed stream of electrons which we term the cathode ray.

The German physicist Goldstein presently devised an ingenious method whereby he demonstrated that such a counter-stream of positively charged electric particles really does exist in a cathode ray. The demonstration was made by piercing small holes in the plate of metal which serves as a cathode, and from which the cathode rays are projected. Through these perforations in the cathode plate, streams of particles moving in the opposite direction to the cathode ray proper, were seen to be projected, producing spots of phosphorescent light on the glass surface of the Crookes tube behind the cathode plate.

Goldstein called these new rays Kanalstrahlen, or canal rays. They were soon subjected to the

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test of deflection by electrical and magnetic influence, and proved to consist of particles very much larger than electrons, charged with positive electricity. The amount of deflection of the rays under the influence of a magnet may be directly observed through the shift of location of the phosphorescent spot on the surface of the glass.

Professor Thomson, who at once took up the subject of these new canal rays, devised a Crookes tube having a phosphorescent screen covered with Willemite at the end back of the cathode plate. He further modified the Crookes tube by constricting it between the cathode plate and the phosphorescent screen, and adjusting electrically charged plates and the poles of a powerful electromagnet about the constricted portion, so that the canal rays must come under the influence of the electric current and the magnetic field in the course of their journey. The effect of the electric current is to deflect the course of the positively charged particles in one direction. while the magnetic influence deflects them in another, so that, under the double influence, they travel in a curved or parabolic path, the exact line of which depends upon the relative strength of the electrical and magnetic influences and the mass and speed of the particles themselves.

The elaborate measurements made with the aid of this apparatus showed presently that the conditions under which the rarefied gas exists in the Crookes tube are much more complex than had at first been suspected. Goldstein's studies of the region near the cathode led him to distinguish five kinds of rays besides the cathode rays. Some of these are evidently secondary ions, pro-

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duced by impact of electrons of the cathode ray against molecules of gas remaining in the tube. Much additional work will be required before the subject is entirely cleared up, but some highly interesting results have already been achieved, in particular by Professor Thomson, with regard to the nature of the canal rays themselves, and to the condition of the atoms of gases within the tube.

THE POSITIVE ELECTRON

It seems to be demonstrated, for example, that the particles that make up the canal rays are not, as was at first supposed, merely gaseous ions from which an electron had been removed. The proof of this was found in the fact that the particles composing the canal rays seem to be of the same character regardless of the kind of gas in the Crookes tube. In other words, Professor Thomson seems very nearly to have demonstrated the existence of a particle of positive electricity which is the same from whatever source it is derived, and which therefore is directly complementary to the negatively charged electron.

Moreover Professor Thomson's most recent experiments have led him to believe that this positive particle is ordinarily linked with the negative particle or electron in the form of a neutral doublet, in which the positive particle forms a center of attraction about which the electron revolves at an exceedingly high rate of speed. He is inclined to believe that the initial effect when a gas is ionized consists in the disruption of such a doublet from the molecule of the gas, and that subsequent collisions among the

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doublets result in the final liberation of the negative electron.

If the observations and calculations upon which this hypothesis is based should be verified, we shall come to know the positive electron as a distinct entity or unit particle of positive electricity, just as we already know the negative electron as the unit particle of negative electricity. While Professor Thomson speaks with characteristic scientific caution, he gave me the very clear impression that he believes quite fully in this positive electron; indeed, he spoke of it as an actuality, and he declared that he believed its structure to be analogous to that of the negative electron. He spoke of the positive electron as being, like the negative, at the end of a magnetic tube or a series of tubes; and as he talked he drew diagrams illustrating how he conceived the negative and positive charge of electricity might neutralize each other when their respective Faraday tubes intersect or come in contact.

PHOTOGRAPHING THE ATOMS

While the unit structures of electricity are thus being investigated in the cathode and canal rays, the more familiar ionized atoms and molecules of gas in the Crookes tube are also made the subject of interesting investigations. Just at the moment of my visit to the Laboratory (November, 1910), Professor Thomson had succeeded in performing the really extraordinary feat of photographing atoms of several gases. He spoke with enthusiasm of this new work, and conducted me to a dark room in the basement of the laboratory, where I saw installed a large Crookes tube, with

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its equipment of electrical plates and magnets as above described, but with an arrangement whereby photographic plates could be substituted for the phosphorescent screen of Willemite.

I was shown negatives on which the ionized atoms of hydrogen, helium, and oxygen, and the ionized molecule of hydrogen (which consists of two atoms) were revealed, each describing a comet-like course, under the combined influence of electrical and magnetic forces, away from a central spot which represented the position of a neutral or un-ionized atom. The electric current has caused the atoms to move upward while the magnetic influence has drawn them to one side. The hydrogen atom is deflected most, because of its light weight, and the hydrogen molecule, the helium atom, and the oxygen atom, each in proportion to its weight, so that the photograph as a whole gives one the impression of four comets flying on divergent paths with the tips of their tails joined.

It curiously stimulates the imagination to view these photographs which thus reveal to actual vision the projected images of particles of matter millions of times too small to be seen through the most powerful microscope, and the very existence of which has often been called in question. As Professor Thomson held up one after another of these negatives for my inspection, pointing out that each different atom took its predictable position in virtue of its known mass, I felt myself in the presence of a veritable wizard among experimenters, who has given us clear glimpses into realms of the infinitely little that till yester-

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day seemed to lie well beyond the confines of possible knowledge.

Lest the reader gain the idea that these studies sweep away all mystery from the material universe, however, let me point out in conclusion that the new knowledge of the electron, illuminative as it is, after all leaves a host of questions unanswered. The electron explains many things, but it remains itself unexplained. In the last analysis it is an utterly mysterious entity, and we are quite in the dark as to its origin and destiny, and as to the real nature of its fundamental properties.

Our theories may explain how electrons build up what we term matter and how their activities produce the manifestations of energy that we term radiant heat, electricity, magnetism, and gravitation. But we still have no inkling as to *why* negative and positive electrons attract each other, while each repelling its own kind. Yet this fundamental fact must remain the basis of all our explanations of the phenomena of matter and of energy.

In other words, what we term, and not without propriety, the "explanation" of sundry mysteries, is seen in the last analysis to be accomplished only by the substitution of other mysteries. In our day the wonder-working electron has been revealed, and numerous riddles of the universe have been proximally solved with its aid; but it remains for the Sir Joseph Thomson of some future generation to explain the mysterious fundamental properties of the electron itself.

CHAPTER VI

SIR ERNEST RUTHERFORD AND THE SCIENCE OF RADIOACTIVITY

IT was only November when I came to Manchester, but a snow-storm was raging that made me feel quite at home. It had all the familiar ear-marks of an Iowa blizzard. It proved to be only an imitation blizzard, however, for the snow melted as it fell, and a truly English slush was under foot. But this only made me feel the more at home for I have lived in England a good deal more than I had in Iowa in recent years.

But after all the weather did not greatly matter. I had come to Manchester not on a meteorological tour of observation, but to see a very remarkable man. I need not have left New York to observe remarkable weather; but I did need to come to Manchester to see Professor Ernest Rutherford.

I found the distinguished physicist in his lecture room at the Physical Laboratory of Manchester University. Somewhat to my surprise, I learned that the scope of the lecture that morning was altogether elementary. Professor Rutherford was explaining certain familiar principles governing the flow of an electric current which go by the name of Ohm's law. He was addressing an elementary class in physics, and he brought the subject home to them by means of apparatus and blackboard diagrams, speaking with as much earnestness and enthusiasm, seemingly, as if he had been expounding one of his latest discoveries before his confrères of the Royal Society.

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After the lecture the students crowded about to ask questions, or to chat with the Professor on some topic of current interest; and I noted that the most admirable spirit of comradeship seemed to prevail between teacher and pupils. I had occasion to observe the same thing later in the afternoon when a company of advanced workers in physics congregated in another room at the laboratory to have tea with Professor Rutherford.

No casual observer would have guessed from any word or act of Professor Rutherford that all the men present were not on the same plane of scholarship and reputation; yet here was a man celebrated everywhere as the foremost authority on the newest branch of physical science; a man whose name is mentioned with admiration in every physical laboratory in the world; a man of whom one of his colleagues has said: "Rutherford is the Faraday of our generation,—the greatest of all physical experimenters; his vision is unerring; he has never made a mistake, and I doubt if he ever will make a mistake."

THE PERSONALITY OF THE GREAT EXPERIMENTER

But while no word or act of Professor Rutherford gave hint that he thought of himself other than as the companion worker of the men who gathered about the tea table, it required no keen observation to note the respect and admiration with which the young physicists regarded their youthful-seeming leader. Nor could any one fail to be impressed at a glance with the personality of the famous physicist.

He is a big man—just above six feet, with broad shoulders and full chest. He has the deep-

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set eye and the keen glance of a man pre-eminently gifted to see things as they are. Every line of his face suggests strength, virility. His aspect is that of a business man rather than that of the traditional college professor. There is a business-like directness about his clear, rapid speech and he shows a business man's interest in affairs of the world. He discussed politics with the students as freely as matters of science, and with as much seeming interest.

Meantime he imbibed freely of strong tea—assuring me laughingly that he brought with him from his native New Zealand a constitution that is invulnerable; and, the tea finished, he took in hand again a black pipe which he declared to be his inseparable companion.

After what I had seen I did not need to be told that Professor Rutherford thrives on work, and that his chief recreation is—more work. He has a limitless fund of inherent energy to draw upon, and he sets himself many a task that a man of different physique might be pardoned for avoiding. As an illustration, his professorship here leaves him entire master of his own time, so that he need not lecture at all—wherefore he frequently lectures twice a day. His experimental researches might very well be expected to command his entire time and thought—whereas he elects to lecture even on elementary topics to beginners.

All this suggests clearly enough that Professor Rutherford's influence is an inspiring one; but only a few college professors would be physically capable of following his example.

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A LABORATORY DEMONSTRATION

Before we came to the tea room, Professor Rutherford had conducted me about the laboratory showing me, among other things of interest, a piece of apparatus that had been devised by the famous Joule, whose epoch-making work on the mechanical equivalent of heat was performed here. But the chief interest of my tour of inspection, of course, centered on the room where Professor Rutherford's own experiments are made. It is a small room with bare brick walls, which one enters with some misgivings, lest one may inadvertently break some of the apparatus, largely consisting of glass tubes that run hither and thither in bewildering array.

"Over here is our chief asset," said Professor Rutherford. "It consists of about fifty thousand dollars worth of radium, which has been loaned to me."

Naturally I looked with curiosity in the direction indicated; but nothing was to be seen there except an earthen receptacle that gave no outward evidence of its precious contents. Glass tubes ascending from this receptacle convey the gas-like emanation that rises from the radium to sundry other receptacles about the room. Some of these glow with a ghostly phosphorescent light when the room is darkened; the casual visitor sees no other evidence of the strange phenomena which are taking place in the glass tubes.

Professor Rutherford took up from the table in the laboratory a small glass bulb which, he explained, had exceedingly thin walls, and in which a portion of radium emanation had been sealed.

"The atoms of radium, as you probably know,"

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he said, "break down into atoms that repel each other and pass into space in the form of a gas which is called radium emanation."

"Discovered and named by you, I recall."

Professor Rutherford shrugged his shoulders deprecatingly and proceeded to make an interesting demonstration.

"Here I have a piece of paper the surface of which is covered with a preparation of sulfid of zinc," he said. "Now we will darken the room and as I bring the screen near the bulb containing the radium emanation, you will see for yourself the effect of the rays that pass out in every direction from the bulb through the thin glass."

As the experiment was performed the little screen glowed with a phosphorescent light when held near the tube. But it was obvious that the influence which produced this effect did not extend to any great distance from the tube, as when the screen was held a few inches away it ceased to glow.

"Of course you know that there are three types of rays coming from a radioactive substance, and that these are called alpha, beta, and gamma rays—the first three letters of the Greek alphabet having been used, when the rays were named, simply because nothing was at that time known as to the nature of these different rays.

"Our chief subject of observation here for a long time has been the alpha ray. Nearly everything new in the science of radioactivity during the past half dozen years has been learned through studying this part of the radiation. The phosphorescence that you see is due to the bombardment of the particles that make up the alpha

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ray—alpha particles we call them—against the screen.”

THE BEGINNINGS OF THE NEW SCIENCE

Our conversation then very naturally turned upon this strange projectile and the things it has revealed. But the interests of the reader will be furthered if before taking these up in detail we outline the main facts of the new science of radio-activity by following in retrospect the story of their discovery.

The facts in question have almost weird significance. They have various implications that have been thought to challenge some of the most firmly established principles of physical and chemical science. They hold suggestions at least of the possible realization of the old dreams of the alchemist; they tell of new and unsuspected sources of energy locked up in the atom that may some day be made available to turn the wheels of our factories; and they enable us to push back at least a little farther the veil that obscures our vision of the intimate and final structure of matter itself.

Let us, then, briefly follow in retrospect the story of the development of this new knowledge, the very inception of which dates from a discovery made so recently as the year 1896.

The initial discovery in question was made by the French physicist Becquerel. The discovery consisted simply in the observation that a certain substance called uranium had the power to affect a photographic plate, somewhat as the X-ray affects it, even when the sensitive surface was protected from the uranium salt by a thin sheet

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of metal. Uranium salts had long been familiar to chemists, but had not previously been known to possess any peculiar characteristics. Becquerel's discovery showed that an influence emanates from them that distinguishes them from any other substance at that time known. As this influence, tested by the photographic plate, suggested a *something* radiating from the uranium salt, this salt was said to be radioactive, and the phenomena associated with it were conveniently classified under the noncommittal term radioactivity. As to *what* the *something* might be to which these phenomena were due, there was at first nothing known.

THE DISCOVERY OF RADIUM

It was soon discovered by the Austrian Schmidt, that the rare element thorium also possessed radioactive properties. Then Professor Pierre Curie and Madame Curie (née Skłodowska) began an epochal series of tests of minerals in which uranium and thorium occur; with the result that in due course they were able to separate from these minerals small quantities of a new substance possessing the properties of radioactivity in a far higher degree than any uranium or thorium salt.

The new substance, which was produced from the mineral pitchblende after an arduous series of chemical manipulations, was christened radium. No other scientific discovery of our generation, with the single exception of the discovery of the X-ray, has been so widely heralded, or has made such appeal to the popular imagination as the

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discovery of this most potent of radioactive substances.

Full credit must of course be given to the discoverers, since their investigation placed in the hands of the scientific world a substance pre-eminently suited for investigating the strange new phenomena; but it should be understood that for the scientific investigation of these phenomena, through which radioactivity has been developed into a precise science, the world is indebted pre-eminently not to the workers who first isolated the radium salt from its mineral matrix, but to that most facile, ingenious, patient, and accurate of investigators, Professor Rutherford, and to the small company of his laboratory assistants and associates working under his direction and within the sphere of his inspiring influence.

Other workers have of course contributed a certain share; but Professor Rutherford has all along been the path breaker, he was first to gain an insight into the true character of the radioactive processes, and first to demonstrate the validity of his premonitions.

PROFESSOR RUTHERFORD'S INITIAL EXPERIMENTS

At the time when Becquerel's initial experiment was made Rutherford was a worker in the Cavendish Laboratory at Cambridge, whither he had come from New Zealand to complete his apprenticeship under the masterful guidance of Sir Joseph J. Thomson. Rutherford's original bent was for mathematics, in which he had specialized at the University in New Zealand; but he early developed an interest in physics, and his sojourn

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at the Cavendish laboratory definitely determined the line of his life work. He turned to the investigation of the phenomena of radioactivity, so he tells us, simply because at the moment when he was beginning his researches this chanced to be the newest and least understood subject before the physical world. Once started he found himself entering upon an alluring pathway from which there has been no temptation to diverge.

As the central theme of study at the Cavendish laboratory had to do with the electric conductivity of gases, Rutherford very naturally began his investigation by testing the effect of the new radioactive substance upon these phenomena. Becquerel had already discovered that the new rays were comparable to the X-ray in their power to ionize a gas. The easy proof of this was found in the fact that the rays would discharge an electroscope. Here, then, was a means—and a much needed means—of testing the rays independently of the photographic plate or the phosphorescent screen.

Experiment showed that this test with the electroscope could be made vastly more delicate than the photographic tests. Ultimately the electroscope came to be employed almost exclusively in studying the new rays, as it permitted tests of exquisite delicacy. Electroscopic tests are indeed estimated to be five hundred thousand times more delicate than the tests that can be made with the spectroscope; yet these in turn are vastly more delicate than the tests afforded by the photographic plate.

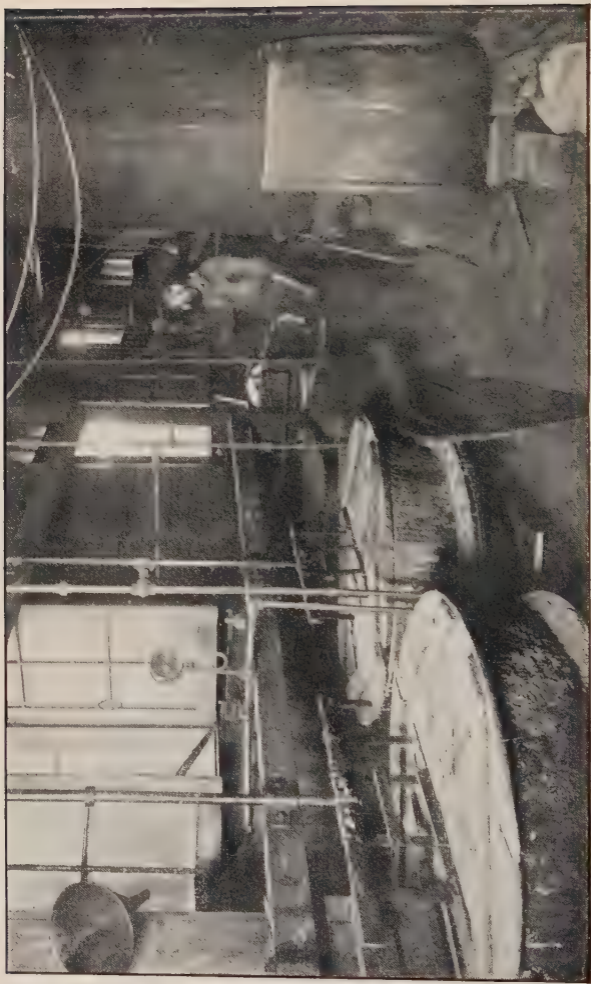
Before Rutherford's experiments had pro-



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A SULFITE MILL (ABOVE), AND AN EARLY MANIPULATION OF A COAL-TAR PRODUCT

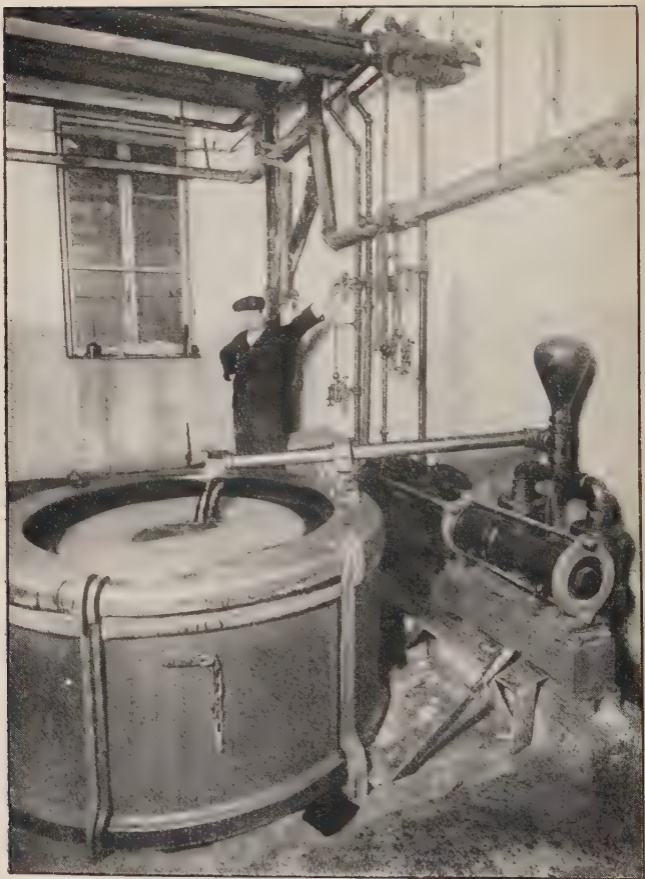


COOKING VATS FOR CHEMICALS

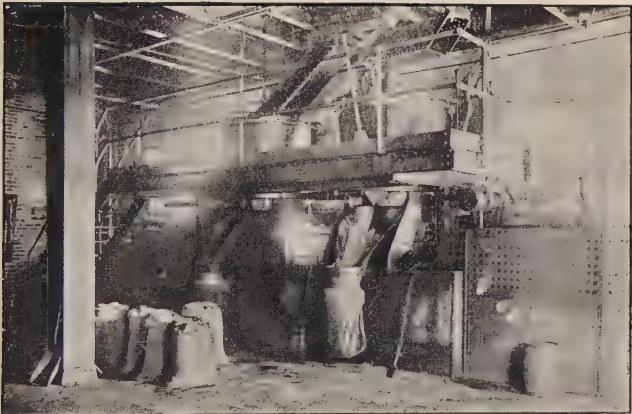


VATS IN A DYE FACTORY

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THE DYEING OF SKEIN SILK



NAPHTHALENE DRYERS AND SACKERS (ABOVE), AND
COOKING VATS AND BAKERY IN DYE WORKS

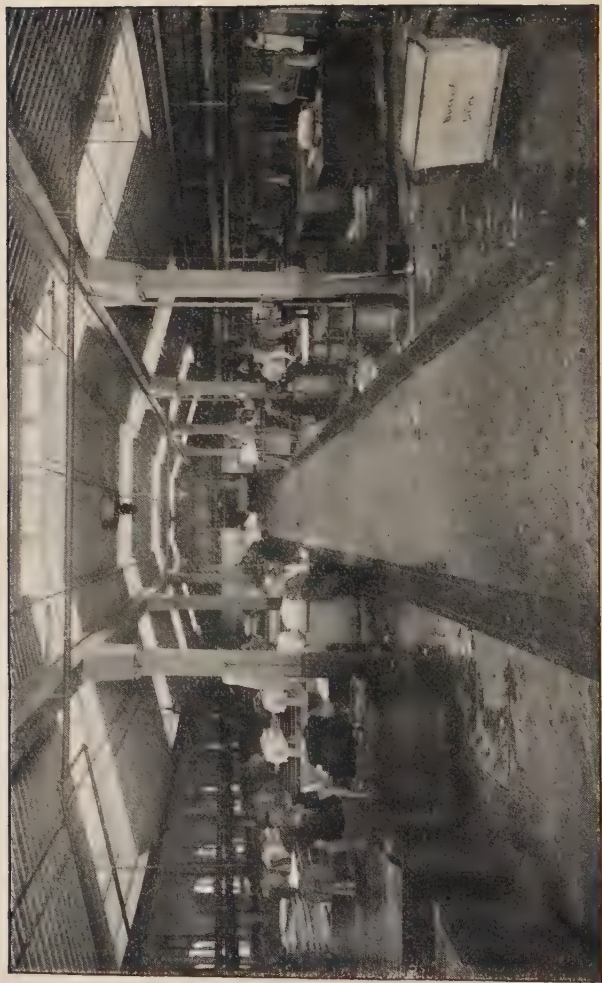


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gressed very far, he was called to the professorship of physics at Montreal, where a notable series of discoveries was made. More recently the seat of his activities was transferred, as already intimated, to Manchester, at which latter place the alpha particle has been made to yield up its final secrets. Professor Rutherford has himself expressed high appreciation of the facilities for research that all along have been given him; but of course the real explanation of his success is to be found in the qualities of his own mind, not in the circumstances of his environment.

THE ALPHA, BETA, AND GAMMA RAYS DISCOVERED

Almost at the outset Professor Rutherford made the discovery that the influence issuing from a radioactive substance is not homogeneous. Proof of this came to light in the course of a test to determine the penetrative power of the rays. The fact that the rays go through substances that are opaque to light was, of course, one of their most novel and interesting qualities. Rutherford found that very thin screens—even a sheet of paper—sufficed to obstruct the portion of the ray that had the greatest power to ionize a gas (and therefore to discharge an electroscope). He gave the name alpha (α) ray to this slightly penetrative part of the radiation.

Another portion of the radiation passed through paper and even through sheets of metal of some thickness. Later experiments showed that it required a sheet of lead about one centimeter (two-fifths of an inch) thick to obstruct it altogether. This more penetrative part of the radia-

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tion was given the name of the second letter of the Greek alphabet (β), and hence came to be known as the beta ray.

That there is yet a third ray far more penetrative than either of the others was not at once discovered, because this portion has but feeble power to ionize a gas; and the radio-action at first tested was relatively feeble, owing to the impurities in the substance first examined. Active tests became far easier after the introduction of radium, which (when isolated as a chlorid or bromid) gives a radiation a million times more intense than the original mineral in which it is found.

When the third ray was finally discovered (by Villard) it was naturally given the name gamma (γ) ray. This ray attracted much attention because it proved to be peculiarly capable of penetrating obstacles. It has relatively small power to ionize a gas; but, on the other hand, its influence on the photographic plate is very powerful; and it makes its influence felt through screens of metal many times thicker than those that suffice to shut off the other rays.

Later tests proved that the gamma ray passes through about eight inches of lead or through more than twelve inches of solid iron. We are becoming accustomed to the observation of this phenomenon, since the X-ray has come to be so much employed in medicine, and so often demonstrated in the laboratory; but the giving out of an invisible ray that passes through lead and iron as freely as light passes through glass seemed utterly mystifying to the entire scientific world a dozen years ago.

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TESTING THE BETA RAYS

Interest naturally centered at first on the more penetrating rays; and in particular upon the beta ray, because this was more easily tested with the electroscope. In 1899 Geisel showed that this ray was deflected by a magnet, proving that it is composed of particles. The following year Becquerel proved that these particles are identical in mass and properties with the unit particles of electricity which J. J. Thomson had just made known to the world under the name of corpuscles or electrons.

In other words, the beta ray was shown to be a stream of electrons, precisely as is the cathode ray in the Crookes tube. The particles of the beta ray are, however, traveling much faster than the cathode particles, their speed being of the same order with that of light, namely, 186,000 miles per second. Their penetrative power is obviously accounted for by their speed, since the momentum of a moving body increases with the square of its velocity.

The greatest possible interest attaches to this identification of the beta ray as a stream of electrons. It proved that radioactive substances at least contained vast quantities of these elementary bodies; and it thus gave a large measure of plausibility to Professor Thomson's theory that the atoms of matter are built up of electrons.

The fact that the electrons making up the beta ray are projected at such enormous speed seemed reasonably explicable on the supposition that these electrons had been revolving at high speed in something like a planetary orbit before being expelled. Just what the force may be that ordinarily

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holds the electrons in their orbits, is matter for speculation or future investigation.

THE GAMMA RAY IDENTICAL WITH THE X-RAY

As the electrons of the cathode ray were known to produce the Roentgen or X-ray, with which physicists had recently become familiar, through impinging against glass or some other substance, it was natural enough to infer that the gamma rays, which showed all the properties of the X-ray, were produced by the impact of the beta particles against the substance of the radium itself. Only the electrons liberated at or near the surface of the radium would escape and be projected into space; those in the interior would be stopped by the parent substance itself, and this presumably would induce the vibration which we call the gamma ray. The highly penetrative character of this ray is doubtless due to the exceedingly high speed of the beta electrons.

Even now, the gamma ray is much less fully understood than the other rays. I asked Professor Rutherford his theory as to its nature.

"It is undoubtedly a very penetrating kind of X-ray," he said, "produced spontaneously in the substance of radium and its allied elements instead of in a Crookes tube."

"But have you a theory as to what this X-ray or gamma ray really consists of?"

Professor Rutherford smiled. "I am not much given to propounding theories," he said. "I deal more particularly with facts. One can't help guessing, but we can hardly say that the matter is settled. Some physicists think the gamma ray will turn out to be made up of minute particles

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of an unknown type; others believe that it is a mere pulse in the ether. The latter view is held by J. J., for example."

"J. J.," it must be explained, is the abbreviation, suggesting at once intimacy and endearment, by which his close friends usually refer to Sir Joseph Thomson.

RUTHERFORD INVESTIGATES THE ALPHA RAY

But if there is still any doubt as to the exact nature of the gamma ray, no doubt whatever attaches to the character of the portion of the radiation that had been given the name alpha ray. A good many workers tended at first to ignore this portion of the radiation because it possessed but a slight measure of the mystical property of penetrating opaque bodies, which property gave the radiation its unique interest. Yet from an early date investigators were not wanting who had an inkling of the importance of this portion of the radiation. In particular Rutherford conceived the idea that here might be found a key to the solution of the bewildering phenomena. The English physicist Strutt (in 1901) and Crookes (in 1902) suggested that the alpha ray, like the beta ray, might be composed of charged particles. Rutherford independently conceived the same notion; and in 1902 he was able to put it to the test.

By placing radium at the bottom of a tube, and arranging a series of slits through which the ray might pass he was able to prove that magnetic and electric influences would deflect the alpha ray so that it impinged against the sides of the tube. This proved that the ray is composed of particles, and these very naturally came to be spoken of as

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alpha (α) particles. The direction of deflection of the particles was opposite to that in which the beta particles are deflected; proving that the alpha particles carry a positive charge of electricity. The relative difficulty with which the ray is deflected showed that the mass of the alpha particle is very large indeed as compared with the mass of the electron.

AN EXTRAORDINARY PROJECTILE

The earliest measurements, indeed, all showed that the alpha particle is of atomic dimensions. It might be a hydrogen atom carrying a single charge of electricity; or it might—as Professor Rutherford thought more probable—be a helium atom carrying a double charge. The latter idea was correct, but it took six years of patient investigation to prove it. In the course of these investigations many highly interesting things were revealed, as we shall see.

Among the most important of those was the development of two distinct methods whereby the alpha particles could actually be counted as they fly out from a radioactive body. By way of anticipation, let us note that the alpha particle, despite its relatively large size, is of such actual dimensions that the number of its fellows that cluster together (at normal temperature) to form a cubic centimeter (two-fifths of an inch) of gas is represented by the following absurd row of figures: 2,560,000,000,000,000,000,000. That is to say, two sextillions, five hundred and sixty quintillions. Understand, please, that this is not a guess or "estimate," but a number obtained by mere multiplication based on actual counting, and

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it will be obvious that the facts with which we are now concerned savor of magic. Yet the methods themselves, once explained, will be seen to be relatively simple.

The first counting of alpha particles was made with the aid of a delicate electroscope utilizing the principle of the ionization of a gas. We have seen that the alpha ray is the portion of the radiation that has by far the greatest potency in ionizing a gas. This is readily understood now that we know that this particle is about four thousand times as large as the electron. It is four times as large as a hydrogen atom, and it starts on its journey at a speed that would carry it about fifteen thousand miles in a second were it not interfered with. An altogether extraordinary projectile that.

But its actual journey is ordinarily a very short one, because it plunges at once among the myraids of molecules of the air, and these presently absorb its momentum and bring it to a stop, just as the particles of a solid ultimately stop a rifle bullet. Meantime the molecules of the air do not escape unscathed, any more than do the particles of the solid into which the bullet is fired. On the contrary, the molecular systems are sadly disarranged, sundry of their electrons having been torn free and projected into space,—much as our earth might be hurtled off into space should a large enough comet come dashing through our planetary system.

COUNTING AND MEASURING THE ALPHA PARTICLES

The atoms of gas thus disrupted by the flight of the alpha particle are said, as we know, to be

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ionized. They become carriers of electricity, and hence discharge an electroscope. The amount of ionization is influenced secondarily by the electrical conditions of the surrounding medium. If the surroundings give opportunity for a free flow of electricity, then the liberated ions move about with such activity that they themselves plunge into neighboring atomic systems and disrupt them, so that large numbers of atoms are indirectly ionized.

Professor Rutherford estimates that by properly adjusting the electric current it is possible to make the conditions so favorable that a single alpha particle entering a gas will set up a commotion that results in the production of something like one hundred thousand ions. The electrical maladjustment thus induced by a single alpha particle can be noted by the discharge of a delicate electrometer.

Accordingly an apparatus was devised (in 1908) which allowed only a very small fraction of the alpha particles given off from a surface to pass through an aperture,—say three or four per minute. The number was counted by actual observation of the motion of the electrometer. It was proved by experiment that the particles fly in every direction with the same frequency; so when the number of particles that pass through a given aperture in a given time had been noted, the total number given off from the measured surface could be readily computed.

INDIVIDUAL ALPHA PARTICLES MADE VISIBLE

The second method of counting the alpha particles was based on the well-known fact that the alpha ray has the property of rendering certain

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substances phosphorescent. It was early discovered that a screen of sulphid of zinc or Willemite furnishes an easy means of testing the existence of this ray. When a portion of the screen is viewed through a microscope, the individual flashes of light, each one indicating the impact of a particle, have been compared to the twinkling stars of the milky way, or to glittering raindrops splashing against a pavement.

The instrument with which this phenomenon is usually observed was devised by Sir William Crookes, and is called a spinthariscopes (from spintharis, a spark).

Professor Rutherford (assisted by Mr. Geiger) modified this instrument in such a way that only observed through the microscope. The number the particles coming through a small measured aperture should strike the screen. The number of splashes of light was then counted, as directly of alpha particles coming from a given surface could then be estimated as before. The numbers obtained by these two quite different methods—one electrical, the other visual—were found to agree within the bounds of experimental error. Thus the number of alpha particles that any given volume of radium gives off in a given time came to be accurately known. As might be expected, the figures are quite mystifying: The number of alpha particles issuing from a single gram of radium *per second* is 136 billion.

THE ALPHA PARTICLE PROVED TO BE A CHARGED HELIUM ATOM

Meantime the evidence all tended to show that the alpha particle is really an atom (or to speak

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accurately, an ion) of helium. Helium gas had been proved by Ramsay and Soddy to be produced from radium. But of course there was a possibility that a helium atom might be sent out from the radium coincidentally with the alpha particle, or independently. It remained to make a crucial test, and for a long time no way was found of doing this.

But in 1908 Professor Rutherford, assisted now by Mr. Royds, made the definitive experiment of letting the alpha particles discharge through a thin glass into an exhausted receptacle. The particles buried themselves in the farther wall of the receptacle, but when they were liberated by the application of heat, the gas in the receptacle gave the characteristic spectrum of helium. This set the matter finally at rest.

That an atom of the element radium should throw out "spontaneously" an atom of another element, helium, seemed almost beyond belief; but the demonstration that it does so was now complete.

The fact that the alpha particle carries two charges of positive electricity may be explained on the assumption that it has lost two electrons. In other words, it is an ion. Recovering two electrons from the ions of matter it enters, it becomes a neutral or normal helium atom. It is interesting to note that the helium atom henceforth, under the conditions that have been tested, maintains its neutrality, and hence exhibits no affinity whatever for any other atom. In other words, helium belongs to the small company of inert gases, which seem to have no capacity for a chemical combination.

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That a chemically inert atom should enter into the composition of a radioactive atom seems doubly anomalous, but it must be recalled that the helium atom, at the moment of its explosion from the radium atom in the form of an alpha particle, conveys a double charge of electricity and hence is not inert. It becomes inert only after it has taken up two electrons from the medium into which it is discharged.

OLD THEORIES OVERTURNED

The question of inertness aside, however, the fact that the helium atom is thus proved to be a component structure of another atom is highly anomalous, and contradictory of our fundamental conception of the nature of the atom. The very word atom implies etymologically something that can not be cut or divided. The atom of each of the elements has been thought by the chemist to be, as it were, a foundation stone of the creation of matter. True, there have been suspicions that the atom might be a compound structure; but never before has a demonstration been made that such is the case. Just what may be the precise significance of the fact that the atom of helium is the one that enters so importantly into the structure of the radioactive atoms, it remains for the science of the future to determine.

The reader will recall that this element helium has a most interesting history. It owes its name to the fact that it was first discovered (by Sir Norman Lockyer) with the aid of the spectroscope, in the sun. For a long time after the discovery it was not known as a terrestrial element. Then Sir William Ramsay in the course of his

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investigations of the newly found atmospheric gases came upon helium in the air brought from a cave; and since then it has been known as a rare gas found in the neighborhood of the mineral deposits that contain radioactive substances. This association is now explained by the fact that the helium is actually produced by the radioactive substances. It must be understood that the alpha particle is identical—that is to say, it is always a helium ion—from whichever one of the radioactive elements, radium, thorium, or uranium, it originates.

COUNTING THE ATOMS

Before we consider further the interesting questions that arise in connection with the helium atom, a very remarkable indirect result of the experiment of counting the alpha particles must be noted. Very accurate tests had been made by Sir James Dewar of the rate of the formation of helium gas from a given quantity of radium. The counting experiments above outlined enable us, as we have seen, to compute directly how many alpha particles (helium atoms) are sent out in the same time by the same quantity of radium. The combined experiments thus tell us the actual number of atoms of helium in a given quantity of gas.

The figures themselves are quite incomprehensible of course (running into sextillions, as already mentioned), but they represent *facts*, and they give us the first positive proof of the exact numbers of atoms in any given substance. Moreover since gases of every kind have the same number of molecules in a given space of uniform

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temperature and pressure, we may now, thanks to the experiment of counting the particles, calculate accurately the number of atoms in a given mass of any substance of known composition.

We may also know the mass of the atom itself by direct computation. The mass of the helium atom, for example, is the portion of a gram represented by a fraction having a denominator consisting of the figures 68 followed by twenty-four ciphers! That makes it "octillions" I believe; but it does not matter greatly how we name the appalling array of figures. The number of atoms in a pinch of salt exceeds the total number of people that have lived on the earth since the human race was evolved. Yet the physicist actually counts and measures these particles, thanks to the alpha particle.

ORIGIN OF THE RADIATIONS

But how are we to account for the observed extrusion of the helium atom from the substance of a body that contains no detectable trace of helium? This was felt from the outset to be a most puzzling question. The answer to it involves the entire theory of radioactivity as put forward by Professor Rutherford, and as now universally accepted.

The theory is that the phenomena of radioactivity are due to the actual disruption of a certain number of atoms of the radioactive body; the initial stage of this disruption consisting of the expulsion of an alpha particle or charged helium atom; as this particle is observed to be expelled at a high rate of speed the natural assumption is that it had been in active motion—presumably re-

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volving about a center—in the parent atom before being expelled. In this connection it is particularly interesting to note that all known radioactive substances have very complex or heavy atoms. The lightest of them is heavier than lead. Uranium is the heaviest substance known. Its atomic weight is 138.5 (the hydrogen atom being the unit).

As the atomic weight of the helium atom is only 4, it is obvious that the loss of one alpha particle from the heavy radioactive atom represents a relatively slight loss of mass. It suffices, however, further to disturb the equilibrium of the radioactive atom. Indeed, it changes the properties of the atom very materially.

In the case of radium, for example, the atom which has lost an alpha particle tends in consequence to repel its fellows, and the new gaseous substance, radium emanation, is formed.

ONE SUBSTANCE CHANGED INTO ANOTHER

But this is only one step in the series of transformations. The atom of radium emanation sends out an alpha particle just as did its parent atom; and it then becomes in consequence what Rutherford christened Radium A. And then in succession are formed substances that were christened Radium B, C, D, E, and F. Each of the substances shows characteristic properties as regards its radioactivity. Radium Emanation and Radium A, for example, give out only alpha rays, whereas Radium C projects also beta and gamma rays; and Radium D has not been observed to give off any radiation at all.

Some of the substances are exceedingly un-

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stable, their "life" being measured in minutes. Others are relatively stable, lasting for hours or days. The last member of the series of daughter products that has been accurately traced is called Radium F, and is identified with the supposed element discovered by Madame Curie before the discovery of radium itself, and by her named Polonium, in honor of her native country.

This Radium F, as tested by Professor Rutherford, is found to be far more active than radium itself,—about 3,200 times as radioactive as radium at its minimum activity, and 800 times as radioactive as "normal" radium. Its activity, however, falls to half its original value in about 143 days. By "activity" it will be understood is meant the rate of sending off of ionizing rays, which in this case consist exclusively of alpha particles.

DOES RADIUM TURN INTO LEAD?

One naturally inquires what remains when Radium F has given out its alpha particles. Obviously it is no longer Radium F. But what is it?

Things move so rapidly in the new science that one can never be sure one is getting the latest information from published matter. So I asked Professor Rutherford what were the results of the most recent work in this line.

"Not quite demonstrative," he said. "We have not quite proved our case. But I am inclined to think that the substance produced when the atom of Radium F fires out its alpha particle ['firing out' is Professor Rutherford's favorite way of referring to the explosion] is an atom of—what do you suppose? Simply the old familiar metal, lead.

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"That seems odd, doesn't it? Radium transformed through a series of intermediate stages into lead."

"It sounds like alchemy," I said.

"Well that is probably what happens; but mind it is not quite proved yet. All the evidence favors it, tho. There is always lead present in all minerals that contain radium; and the atomic weight of lead is just four units below what we believe to be the atomic weight of Radium F,—as it should be, after Radium F has discharged its helium atom, the weight of which is four."

THE ORIGIN OF RADIUM

"How long does it take for a given quantity of radium to be transformed into its daughter particles?"

"We can only estimate it, of course; but we can do that pretty accurately, now that we know the rate at which the helium ion is thrown out and the total number of radium atoms. In round numbers it works out at about 1800 years."

"Then no particular portion of radium that we discover to-day has been in existence as such, longer than about since the beginning of the Christian Era?"

"Apparently not."

"Obviously, then, radium itself must be constantly forming out of something else?"

"Just so; and we have very recently discovered what that something else is. We got on the track of it some time ago, and now Mr. Boltwood has found it and named it ionium. This is of course a radioactive substance. In breaking down it forms radium. Ionium in turn is the product of

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a line of substances leading directly back to uranium, which, as you will recall, was the original radioactive substance discovered by Becquerel. The whole story of the line of descent carries us from Uranium through Radiouranium, Uranium X, Ionium, Radium, Emanation, and its successive daughter substances to Polonium, and then (with just a possibility of doubt), to lead.

"The atomic weights of these successive substances confirm the supposed facts. The uranium atom is the heaviest of all known atoms, weighing 238.5; the weights of the intermediate products fall off in regular sequence, including radium at about 226, and reaching polonium at about 210,—the known weight of lead being 206.5. But regardless of this it is the observed fact that the origin of radium is due to a series of transformations beginning with uranium."

"Beginning?" I queried.

"Well of course we do not know anything about *beginnings* in the final sense of the word. But so far as present knowledge goes uranium is the initial substance. It is conceivable that uranium may be a product built up of the combination of other substances. We have no experimental knowledge of such a case of atom building; but neither had we any knowledge of the breaking down of atoms until uranium itself was discovered. Our knowledge of the whole subject is in its infancy."

BREAKING UP THE ATOM

Since the time of my visit, Professor Rutherford (now Sir Ernest) has gone to Cambridge University; but as a matter of course, he is pur-

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suing his specialty with unabated zeal, after the inevitable war-time interruptions. Among other things, he has made elaborate series of investigations to discover just what happens to the atoms with which the hustling alpha particles come in contact.

The tests in question have been made by placing a luminescent screen as a target well beyond the range of the alpha particles. Under such conditions, it is observed that when the alpha particles are discharged into an atmosphere of hydrogen, of oxygen, or of nitrogen, the luminescent screen reveals the impact of the particles which can be explained only on the supposition that the impact of the little projectile has produced a tremendous commotion among the atoms, causing some of them to hurtle off to a distance far beyond the range of the alpha particle itself. In the case of the nitrogen atom, it is more than suspected that actual disintegration has taken place, a portion of the substance of the atom being torn away. This disrupted portion is believed to be the equivalent of a hydrogen atom. It is said that the evidence is not quite conclusive, but that it establishes a high degree of probability.

This suggestion of the disruption of the atom of an element, had it been made a few years ago, would have seemed so revolutionary as to startle the entire scientific world. But to-day, thanks largely to the antecedent work with radioactive substances, the conception of the atom as a complex structure has practically supplanted the old idea of the atom as the ultimate and indivisible particle of matter. So the apparent disruption of the nitrogen atom by the impact of the alpha

particle will be provisionally accepted as an interesting additional item of scientific knowledge, tending to corroborate the new conception of the nature of matter, but in no wise disturbing the equanimity of even the most conservative of chemists or physicists.

HAS THE "PHILOSOPHER'S STONE" BEEN FOUND?

Then it has been reported that Professor Rutherford has succeeded in making gold in the laboratory by transmutation. The precise method employed has not been revealed, but it may be assumed that the experiments in this connection were conducted with the aid of radium or its allied elements.

Such a report does not come to the world of science nowadays as anything very startling or even unexpected.

From a strictly scientific standpoint there is no greater interest in the genesis of gold in the laboratory than in the production of any other element; but there are obvious practical bearings of such transformation that give it tremendous popular interest. It must be understood, however, that Professor Rutherford's observation, if valid—and his observations in the past always have proved to be valid—have no commercial bearings at the present time, inasmuch as the laboratory production of gold is far more expensive than production by the ordinary process of mining.

It does not follow, however, that less costly methods may not be found. Conceivably as a sequel to the experiments under consideration, gold may be made with such facility that the entire structure of the mechanism of commerce

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may be modified through the necessity for the adoption of a new standard of measurement.

The elements which might plausibly be expected to furnish material for the making of gold are bismuth, lead, and mercury, these being the only common elements that are heavier than gold. The atomic weights are: gold 197.2, mercury 200, lead 206.9, bismuth 208.5. The less-familiar element thallium, with the weight of 204.2, falls within the same group. In the same scale the atomic weight of helium is 4.

The relation of gold to mercury and lead and bismuth is therefore not such as to be explained by the inclusion in the heavier metals of one or two or three helium atoms respectively; yet it is suggestively near that relation. Bismuth, for example, outweighs gold by 11.3 points; whereas three helium atoms represents 12 units of weight. If lead, itself produced by the extrusion of helium atoms from heavier radioactive substances, could be made to give up the equivalent of two helium atoms the product would closely approximate the atomic weight of gold. But of course close approximations do not count in the world of chemistry. So some additional atom juggling is required.

Perhaps Professor Rutherford has found out just what this is, and just how it is to be accomplished. That the thing does occur under natural conditions, or has occurred sometimes in geological history, is strongly suggested not merely by the atomic weights themselves, but by the fact that the native amalgam of mercury with gold has sometimes been found; that bismuth from South

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America is sometimes rich in gold; and that the lead ore known as galena is almost always gold-bearing.

The transformation through which the elements we now observe have been brought in their present condition have largely taken place in the depths of the earth, where conditions of pressure exist that the chemist can not duplicate in the laboratory. It has been experimentally proved that when carbon is subjected to great pressure by inclusion in a congealing mass of iron, it may crystallize in the form of diamonds. It has been plausibly suggested that under the conditions of the almost inconceivable pressure that exists in the interior of the sun (it is computed at the depth of a thousand miles the pressure is nearly six million tons to the square foot), atoms may be disindicated.

It is by no means certain that the same thing may not occur in the central structure of our globe. Indeed, it is within the possibilities that the entire central core may be in a condition of elemental flux in which the condition of radioactivity and transmutation are universal. Possibly it is only such portions of the mass as come near the surface and are cooled and released from extreme pressure that assume the fixed form to which we give the name of elements.

The validity of such assumptions can be tested only when new laboratory methods are developed; but studies of radioactivity take us a step in the new direction and already have served curiously to rehabilitate the almost forgotten dreams of the alchemist.

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IS ALL MATTER RADIOACTIVE?

We have dealt chiefly with radium, but it must not be forgotten that there are at least two other radioactive substances known; or to speak more in accordance with recent knowledge two *families* of substances. One of these is the thorium group, the other the actinium group. Each of these has been proved (chiefly by Professor Rutherford) to represent a series of transformation products. Thorium, for example, produces in turn, mesothorium 1, mesothorium 2, radiothorium, thorium X, emanation, and thorium A, B, C, and D. Actinium produces a similar series; and actinium is genetically connected with uranium, tho the precise relationship has not yet been closely traced.

The total number of radioactive substances included in the three families is no fewer than thirty. Each of these transformation products, as Rutherford points out, is in effect an element according to ordinary chemical standards.

Finding thus so large a number of radioactive substances, the question has not unnaturally suggested itself as to whether all matter is not in some degree radioactive. The wide distribution of radium and its allies; proof that radioactive matter enters to some extent into the composition of many rocks, such as granite, basalt, and serpentine; the finding of radioactive qualities in some of the mineral springs, in the substances of the earth, and even in the atmosphere—these observations, as at first revealed, led many physicists to suppose that all matter may be more or less radioactive.

The idea is startling to the last degree, for it amounts to the suggestion that all matter is being

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transformed into simpler and simpler atoms, and scattered out into space in the form of the inert helium atom; and that the electrical energy that lies at the foundation of all chemical action is being similarly dissipated. Considering the subject thus, one's imagination begins to picture a universe frittering itself away and dissolving into nothingness.

Let it be said at once, however, that the balance of experimental evidence is against the validity of this hypothesis. It is difficult to prove a negative, but the best current opinion is that the atoms of most substances have attained a stage of stability and are not undergoing decay in the manner of radium and its allies. Sir J. J. Thomson suggests that each kind of non-radioactive matter, as we know it, probably represents the end of a series of radioactive transformations undergone in the past.

It may occur to the reader that the ionization of an ordinary atom or a molecule of gas is a phenomenon similar to the disruption of the radioactive atom. In one sense it is so, inasmuch as ionization is accomplished by the thrusting out of one or more electrons from the substance of the atom. But it must be noted that the electrons liberated in the ionized gas, while exactly the same as the beta particle in character, differ in regard to their speed of flight. The motion of these ionized electrons is so slow that Professor Thomson has suggested distinguishing them by the name of delta (δ) rays.

Professor Rutherford suggests that these electrons were probably outlying planets, so to speak, of the atomic system, and that for this reason

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their loss does not disrupt the atom. In point of fact, as we have seen, the gaseous ions quickly recombine and the atoms from which they came are then as stable as before.

The electrons of the beta ray, by parallel reasoning may be supposed to owe their speed to a more central position in the atomic system. At all events they were held in position by stronger forces; they travel with far higher speed when once liberated; and their liberation is accomplished by the permanent transformation of the atom.

HOW RADIUM HEATS ITSELF

All these glimpses into the structure of the atom suggest, as do the radioactive phenomena in general, that the atom of matter is not only an exceedingly complex structure but one in which there is a tremendous concentration of energy.

Experimental proof as to the latter point was furnished in 1903, when P. Curie and M. Laborde discovered that radium is a self-heating substance. It was found that a given quantity of radium gives out perpetually enough heat to melt its own weight of ice every hour. Professor Rutherford estimated that if the substance of the sun were one per cent. radium, the heat of that body would be accounted for.

The amount of heat given out is the same whether the radium is kept in a surrounding medium that is hot, or whether it is sunk in liquid hydrogen at only a few degrees above the absolute zero of temperature. Hour after hour and year after year, the radium continues thus to give out heat throughout the term of its existence.

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When this fact was first discovered, it was so anomalous that it fairly staggered the belief of the scientific world. Some physicists did not hesitate to declare that this phenomenon sufficed to overthrow the great central doctrine of conservation of energy, which is one of the most fundamental and all-encompassing laws of the mechanical world.

But such a view was soon seen to be ill-considered. Almost immediately Professor Rutherford suggested an explanation which brought the phenomena of heat production (as well as the phenomena of light production—for radium is self-luminous) within the scope of recognized physical laws, while at the same time giving us new insight into the character of the forces that operate in the atom.

He suggested that the heating effect is due simply to the impact of alpha particles on the radium itself.

"Consider for a moment," he says, "a pellet of radium encased in a tube. The alpha particles are shot in great numbers equally from all parts of the radium, and in consequence of their slight penetrating power are stopped in the radium itself or by the walls of the tube. The energy of motion of the alpha particle is converted into heat. Under this view the radium is subject to a fierce and unceasing bombardment by its own particles, and is heated by its own radiation."

The work of Rutherford and Barnes in 1903 confirmed this view. They showed that three-quarters of the heating effect in radium is due to emanation, and that each of the different substances produced in succession gives out heat in

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proportion to the energy of the alpha particles expelled from it. These experiments reveal the enormous store of energy drawn upon. Rutherford calculates that "one kilogram (about a quart) of radium emanation and its products would initially emit energy at the rate of 14,000 horse power, and during its life would give off energy corresponding to about 80,000 horse power for one day."

IF THE ENERGY OF THE ATOM COULD BE UTILIZED

Here, then, is a vast storehouse of energy in the atom of which science has hitherto had no knowledge. Nor can we suppose that these radioactive substances have any monopoly of this supply of energy. On the contrary, we must suppose that the components of any atom of matter, of whatever kind, are similarly held in place by the interplay of tremendous forces that seem utterly disproportionate to the size of the structure involved.

Sir Joseph Thomson has suggested that a piece of radium the size of a pea has a store of energy, could we draw on it at will, capable of propelling a steamship across the ocean. Similarly every granite pebble stores a supply of energy that would turn the wheels of the largest factory,—if we knew how to liberate the energy thus stored.

When I talked with Sir Joseph Thomson about this, he called my attention to the fact that our means of experimenting are at present exceedingly restricted. "It is true," he said, "that we can not at present influence the rate of activity of a radioactive substance, much less produce artificial disruption of more stable atoms. But you

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must recall that the range of temperature, for instance, to which we can now subject any substance only varies from the cold of liquid hydrogen to the heat of the arc light;—that is to say, by only a few thousand degrees. But the flying electrons of the beta ray give us an intimation of energy corresponding to millions of degrees. If we ever learn how to get really high temperatures in the laboratory, we may be able to influence radioactivity, or to get at the energy of atoms in general.”

That surely suggests alluring practical possibilities. No more bother about the coal supply. No troublesome shackling of the Niagaras. Nothing necessary to gain a supply of power but to liberate the energy in the first chance pebble that comes to hand, or for that matter in a bucketful of earth.

It all sounds very visionary. Let us admit that it is visionary in the present state of our knowledge. No one has at present any notion as to how such an unlocking of the atomic storehouse of energy may be accomplished. But it is something to know that the storehouse exists; and I for one do not doubt that science will ultimately find a way of making it available. The entire economic structure of civilization will be revolutionized should this come to pass.

LIBERATING ATOMIC ENERGY

In 1921 announcement was made in a New York newspaper of a cablegram from Berlin telling of a discovery said to have been made by a Leipsic engineer—no less a discovery than a way to break up the atom and liberate its energy.

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If authentic, this message would have been far and away the most important one that ever was flashed along a wire. But the message carried its own refutation in the statement that negotiations were pending whereby a British syndicate was to secure foreign rights to the discovery for a million pounds sterling.

That statement was about as plausible as if it were announced that the British government had decided to dispose of its entire navy, and that all its battleships had been offered to the United States for the sum of one cent. For in the first instance, if such a discovery had been made in Germany, the secret would not be purchasable outside of Germany at any price until the entire world had accepted submissive peace terms at Germany's dictation; and secondly, the price of the secret would ultimately be named not in millions but in billions of pounds sterling.

So it was no matter for surprise that the message telling of the discovery was supplemented with the statement that the alleged discoverer had been proved to be a swindler and promptly landed in jail. Evidently the authorities in Germany are not in a mood to be trifled with on such a subject.

Doubtless there are many men of science in Germany and elsewhere whose thoughts are directed towards the possible solution of the problem of breaking up the atom. We have received the evidence that every atom of matter is a storehouse of energy and hence a possible source of power if only the way could be found to make this energy available. The amount of energy involved, as estimated, is almost unbelievably great—considering the size of the atom.

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According to one calculation, the repulsive power that is inherent in the so-called electron, which is the building stone of the atom, is a trillion-trillion times greater than the attractive power of gravitation.

It is stated that if a single gram of electrons (an ordinary pea weighs about a gram) could be isolated and placed at the North Pole and another gram at the South Pole, the two masses of electrons would repel each other with the force of 112,000,000 tons, notwithstanding the fact that the force decreases with the square of the distance.

It would appear that if the two little pellets of electrons could be placed near together at the center of the earth, they would scatter our entire globe into fragments.

However much we may qualify these estimates, the fact remains that enormous power is inherent in the electron. Under existing conditions, this power is not exhibited (so the physicists believe), because every atom has at its core a charge of positive electricity that balances the negative electricity of the electrons and holds them in thrall-dom, somewhat as planets are held by the gravitational pull of the sun.

All that is necessary, apparently, is to neutralize the positive electricity in the atom—and the electron would do the rest. Up to the present, however, no one has the remotest conception as to how such neutralization might be effected. One of these days someone may find the way. Then the entire structure of civilization—social, economic, and military—will be revolutionized. Schemes for harnessing the rivers and cataracts

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to secure power will be forgotten; coal mines and oil wells will be abandoned; and dynamite and T. N. T. and the allied explosives of today will be as children's toys compared with the new explosive power that can be liberated from any fragment of matter—since all matter is composed of atoms. A pea-sized fragment of matter (See Sir J. J. Thomson's estimates above cited) would furnish energy to drive the largest ship across the ocean, or to send an airship ten times round the world. A bucket full of pebbles, scattered from the airship, might devastate a continent.

It is hardly probable that men of authority took seriously the announcement of the controlled—and commercially negotiable disruption of the atom. But, on the other hand, it was only twenty-five years ago that there came out of Germany an announcement that seemed more miraculous than the unlocking of the storehouse of the atom would seem now—namely, Roentgen's discovery of the X-ray. That discovery may be regarded as the first step in a series of invasions of the atom that will ultimately lead to entire conquest of the realm of the infinitely little. But the date of final conquest is likely to be 2023—or perhaps 3023—rather than the present year.

CHAPTER VII

ASPECTS OF SYNTHETIC CHEMISTRY

FROM ANALYSIS TO SYNTHESIS

WE HAVE been concerned chiefly in the preceding chapters with the attempt to tear the atom apart and look into its interior—as becomes the explorer. We have seen that the trend of modern thought is toward the conception of the atom as a composite structure, and we have somewhat attentively examined the evidence on which that tendency is based.

We shall revert to this aspect of the subject in a later volume, when questions of energy in its relation to matter are under discussion. But we must not here leave the atom, even temporarily, without adverting to a quite different aspect of the part played by this infinitesimal structure in the laboratory of the modern chemist.

In other words, we must briefly refer to the cognate subject of synthetic chemistry. Merely to analyze is important—indeed, essential. But the ultimate object of analysis is to supply data for synthesis. We tear down in order to learn how to build up. And in the latter field, the modern chemist has accomplished wonders.

It should be clearly understood, however, that the synthetic chemistry now in question is not concerned with the building up of atoms. For its purposes, the atom is the primordial, unchangeable thing that it seemed to earlier generations.

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It is a unit structure; a primordial building stone, having certain attributes that never change in themselves, however varied the manifestations of physical appearance that may be taken on by the products of varied combinations of atoms.

COAL-TAR AS RAW MATERIAL

For example, the synthesizer builds multitudinous structures with groups of carbon atoms, hydrogen atoms, oxygen atoms, and nitrogen atoms. He finds them, let us say, grouped in such wise that they make up a black, sticky, malodorous substance called coal-tar. He distils this substance and gets various and sundry quite different products, notably those that he names benzene, toluene, xylene, phenol, naphthalene, anthracene, and pitch. By carrying the process a little farther, he substitutes for the pitch certain substances that he calls methyl anthracene, phenanthrene, and carbazol.

The ten substances bearing these odd names are termed "crudes,"—that is to say, they are the relatively crude materials into which the coal-tar has been broken. They will serve as basal raw materials for the various manipulations which the chemist has in contemplation.

When these manipulations have been carried out, in one direction or another, the most extraordinary range and variety of new products may have been built from this raw material. We may have the most destructive of modern high explosives, such as trinitrotoluol (T. N. T.) and lyddite; or the most beautiful of "aniline" dyes of myriads of gradation of shade and color; or countless varieties of white crystals to be used as

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medicines, including such familiar examples as aspirin and phenacetin.

THE UNCHANGING ATOM

And the marvel of it all is that these utterly different substances—totally unlike in appearance, in apparent constitution, and in their reactions to enviroing conditions—are still constituted, part and parcel, of the same original elements. They are still compounds of the original atoms of carbon and hydrogen (plus certain others) that made up the substance of the coal-tar. And from first to last, each and every one of these atoms has maintained its individual identity and its own particularities of habit.

Every hydrogen atom, for example, has demanded that it be permitted to join hands with a single partner; whereas every carbon atom has just as insistently demanded four partners—with the proviso that a fellow-atom with two hands might count as two partners. (See section on Valences in Chapter I.) There has been no question at all of the changing of atomic properties, much less of the breaking up of individual atoms. Indeed, the chemist who made the manipulations that brought about the transformations would have been utterly at sea had he not felt full assurance that each and every atom, however placed, would remain true to its traditions, responding in a predictable way.

Predictions as to what an atom will do under new conditions are of course based largely on what it has been observed to do under more or less similar conditions. But the fundamental basis for expecting certain reactions is the knowl-

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edge of the varied affinities and valences of the various atoms involved. The chemist knows these things just as an architect knows the properties of bricks and mortar and wood and steel. And his work of construction may with validity be compared to that of the architect.

As Dr. Edwin E. Slosson has said, in his fascinating book, *Creative Chemistry*, the modern synthetic chemist is not a discoverer, he is an inventor. He designs a new dye or drug or noxious gas, to have certain predicted properties, somewhat as an architect designs a building.

And just as the architect has always in mind a few basal principles, and a few type-forms (for example, rectangles and arches), so the chemist has before his mind's eye—and for that matter on paper—a certain type-form of molecular architecture, involving a very fundamental combination of carbon and hydrogen atoms. This framework he calls a benzene ring, or hexagon.

THE BENZENE RING

This famous structure is usually drawn as a hexagon.

There is a carbon atom (represented by a capital C) at each corner; and to each of these carbon atoms there is exteriorly attached a hydrogen atom (represented by a capital H). The sides of the hexagon are lines that represent valences, or bonds of affinity, and for three of the sides these are double lines. A single line joins each hydrogen atom to its carbon mate. Closer inspection shows that each carbon atom is held to its contiguous carbon associates by two bonds on one

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side and one bond on the other; its fourth bond (valency) being satisfied by the hydrogen atom.

This ring is known as the benzene ring, because it represents the molecule of the chemical benzene (not the familiar benzine used to clean clothes), which, it may be recalled, is one of the "crudes" developed by distillation of coal tar.

The creative chemist never gets far away from the benzene ring. He has it pictured before him as the basis of all his architectural plans. In Dr. Slosson's graphic phrase, he "rubs out an H and hooks a nitro group (NO_2) on to the carbon in its place; next he rubs out the O_2 of the nitro group and puts in H_2 ; then he hitches on such other elements, or carbon chains and rings as he likes. He works like an architect designing a house and when he gets a picture of the proposed compounds to suit him he goes into the laboratory to make it."

Dr. Slosson goes on to tell how the nitro group is introduced by boiling some benzene with nitric and sulfuric acids; and how the nitro-benzene ($\text{C}_6\text{H}_5\text{NO}_2$) is treated with hydrogen, which displaces the oxygen, and gives $\text{C}_6\text{H}_5\text{NO}$, which is aniline, the basis of any number of compounds that are called "aniline dyes" because of their origin—tho aniline itself, rather paradoxically, is not a dye but a colorless or brownish oil.

A MOLECULAR SKYSCRAPER

The intricacies of the ultimate architecture are illustrated by Dr. Slosson's exhibition of the diagrammatic formula for the molecule of one of the coal-tar dyes which he introduces as "not one of the most complicated but still complicated

EXPLORING THE ATOM

enough;" a diagram that stretches clear up and down the page—seven benzene rings piled one above another, with hydrogen atoms above and below and two entresols of the same, making a veritable skyscraper of a building.

Yet this elaborate structure has been upraised for the most part by merely adding more and more of the original materials, carbon and hydrogen, as represented in the benzene ring. Of the more than four score atoms that enter into the completed design, we find only these intruders: five nitrogen atoms, nine oxygen atoms, and three atoms each of sulfur and sodium.

The chemist names the compound sodium ditolyl-beta-naphthylamine-6-sulfonic-beta-naphthylamine-3.6-disulfonate. And Dr. Slosson assures us that this is highly intelligible to the initiated; that, in short, an expert in dyes, after seeing the name, could draw its picture, and tell how it was made and how it would behave.

After all, he says, truly enough, the name is no more of a mouthful than "Third Assistant Secretary of War to the President of the United States of America." The trade name of the dye, Brilliant Congo, is easier to say, but does not mean anything. Still it is hardly to be expected that the public at large will familiarize itself with so technical a nomenclature. The usual compromise, as one may see by examining the labels on the bottles of a good many synthetic drugs in common use, is to give the trade name in large letters and the hyphenated descriptive formula in smaller script below.

Our present concern, however, is not with nomenclature or formulas, except as they illus-

WHY RADIUM IS COSTLY

trate the principle that chiefly claims attention—the principle of atomic individuality and stability. The point to be emphasized is that our brief survey of the methods of the synthetic chemist who deals with carbon compounds has shown us that multitudinous physical substances may be compounded of the same elements in various proportions and combinations, while the elements themselves retain their pristine qualities, absolutely resistant to any forces of disruption or transmutation that the present-day laboratory worker can bring to bear upon them.

DYES, EXPLOSIVES, AND PROTOPLASM

The illustration gains in vividness if we add that the same benzene ring we have just been studying is the basis of other compounds that the chemist can analyse but can not as yet construct. Protoplasm itself, the basis of all living tissues, vegetable or animal,—the foundation-structure of every living cell,—is merely a more intricate labyrinth of benzene rings, elaborately honey-combed and enmeshed with a certain number of added atoms of oxygen and nitrogen chiefly, and a small sprinkling of atoms of other types, including sulfur.

The correspondence in general formula between the aniline dyes and high explosives on one hand and protoplasm on the other has long excited the interest of the chemist. He hopes some day to be able to build the protoplasmic molecule, with its two thousand or so atoms. The building of synthetic dyes and drugs and explosives is a step in that direction. He has even taken a longer step, by building so-called polypeptids, which are de-

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composition products of protein (protoplasm) when hydrolized. But as yet he is not able to go beyond that.

His position is comparable to that of an architect who has learned to build a ten-story structure but is not competent to compute the specifications for a Woolworth Building. He knows what materials are needed, and even the proportions in which they must be supplied. But he does not as yet know how to "rub out and substitute" enough times over and over and always in the right places. And even if he were to develop a correct formula, he would not know just how in practise to effect the necessary combinations and substitutions.

These are things that must be learned by future experience. Meantime, the work with dyes and drugs and explosives is providing a training without which the would-be synthesist of protoplasm could no more hope ever to succeed than a carpenter trained only in the construction of small frame dwellings could hope to create a fifty-storied skyscraper of steel and concrete.

APPENDIX

WHY RADIUM IS COSTLY

WHEN we are told that radium is the costliest commodity in the world, we naturally ask why it is so costly.

The answer is somewhat surprizing. It appears that radium is costly, not primarily because it is so rare, but because so much time and skilled labor are requisite for its extraction from the crude ores in which it is originally found. These ores, to be sure, are not abundant, except in a few localities; but there are regions—notably out in Colorado—where thousands of tons of radium-bearing stone, looking not unlike a yellowish limestone, may be mined at no inordinate cost. The difficulty is that this ore has no practical value until it has been subjected to expert treatment involving a series of manipulations extending over several months.

The search for the proverbial needle in the haystack is a comparatively simple task in contrast to the task of extracting, let us say, five milligrams of radium from a ton of carnotite. A milligram, it will be recalled, is the thousandth part of a gram; and a gram is about the thirtieth part of an ounce. The task is so difficult that it is not commercially feasible unless a given ton of ore has at least \$500 worth of radium incorporated in its substance.

There are thousands of tons of ore containing, say, \$200 or \$300 worth of radium to the ton

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piled up as waste material near the Colorado radium mines, simply because in the present state of our knowledge the expense of extraction would be greater than the value of the radium. Yet each pound of this waste material contains radium enough to purchase several pounds of sugar, if only it were isolated.

A comparatively small part of the ore dug up at the radium mines is rich enough to be worth "working." This is broken into fragments that can be packed into hundred-pound sacks, like so much coal, and shipped in carload lots to the factory where extraction is to be effected. The United States Radium Corporation has such a factory at Orange, New Jersey. There one finds a series of buildings with some lofts containing great vats suggestive of a brewery; other rooms with furnaces and apparatus reminiscent of a smelting plant; and still others showing series of great tub-like receptacles like nothing that one has seen elsewhere.

The tanks, we learn, contain the ground radium ore in a bath of sulfuric acid which will extract a considerable part of the radium in the form of a sulfate, mixed with various impurities, including barium and vanadium. The liquid is drawn from one vat into another, and in the course of a month or two the radium and barium sulfates, intermingled, have settled to the bottom, and the vanadium, in solution, may be drawn off, and reduced ultimately to a form in which it may be sold for use as an alloy in making certain kinds of steel, constituting thus a somewhat valuable by-product.

Meantime the radium and barium sulfates,

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shoveled up from the bottom of the tank, will be transferred to the oven-room, there to be baked in such a way that the sulfates are transformed into carbonates; the latter being soluble, as the former are not, in the hydrochloric acid bath to which the product will next be subjected.

A long and tedious process ensues in which part of the radium, still associated with the barium, crystallizes out of the acid solution, now in the form of a chloride; to be redissolved and recrystallized over and over, and finally transferred to yet another series of receptacles, this time containing hydrobromic acid, which effects the final transformation into radium bromide.

And finally, in a small, sparsely furnished laboratory at the end of one of the buildings, after three or four months of journeying, arrives what is left of thirty or forty tons of material, in the form of a little deposit of flaky crystals, in the bottom of an ordinary glass finger bowl. You could scrape the whole of it up in a tablespoon.

Verily, a mountain in labor has produced a mouse. But the mouse is worth, let us say, half a million dollars!

And the end is not yet. It still remains to purify the product by redissolvings and recrystallizations, until perhaps a scant teaspoonful of a white powder, radium bromide, remains as the net product of a month's activity of the entire factory. And in the ultimate room—the sanctum sanctorum—we find a skilled chemist, Dr. E. D. Leman, seated at a plain laboratory table, with nothing to suggest the unusualness of his task except the fact that his face is masked with a

EXPLORING THE ATOM

towel, and his body protected by a little barricade of lead plates, which might stop a bullet, and will in fact intercept millions and millions of little bullets known as alpha particles and still smaller ones called electrons that are incessantly sent out from the match-sized tube of radium he is handling. Even the lead will not altogether screen him from the penetrating "gamma" rays which are in effect a form of X-ray, but it will sufficiently attenuate them to make them relatively harmless.

As your mind reverts to the shed where the crude ore is stored like great coal heaps, and you now reflect that the tiny tube the chemist is handling contains all that was sought in several tons of the raw material, you feel that you comprehend why radium is marketed at one hundred dollars per milligram.

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